Bending the Pollution Curve

An Analysis and Prioritization of Pollution Management in Ethiopia

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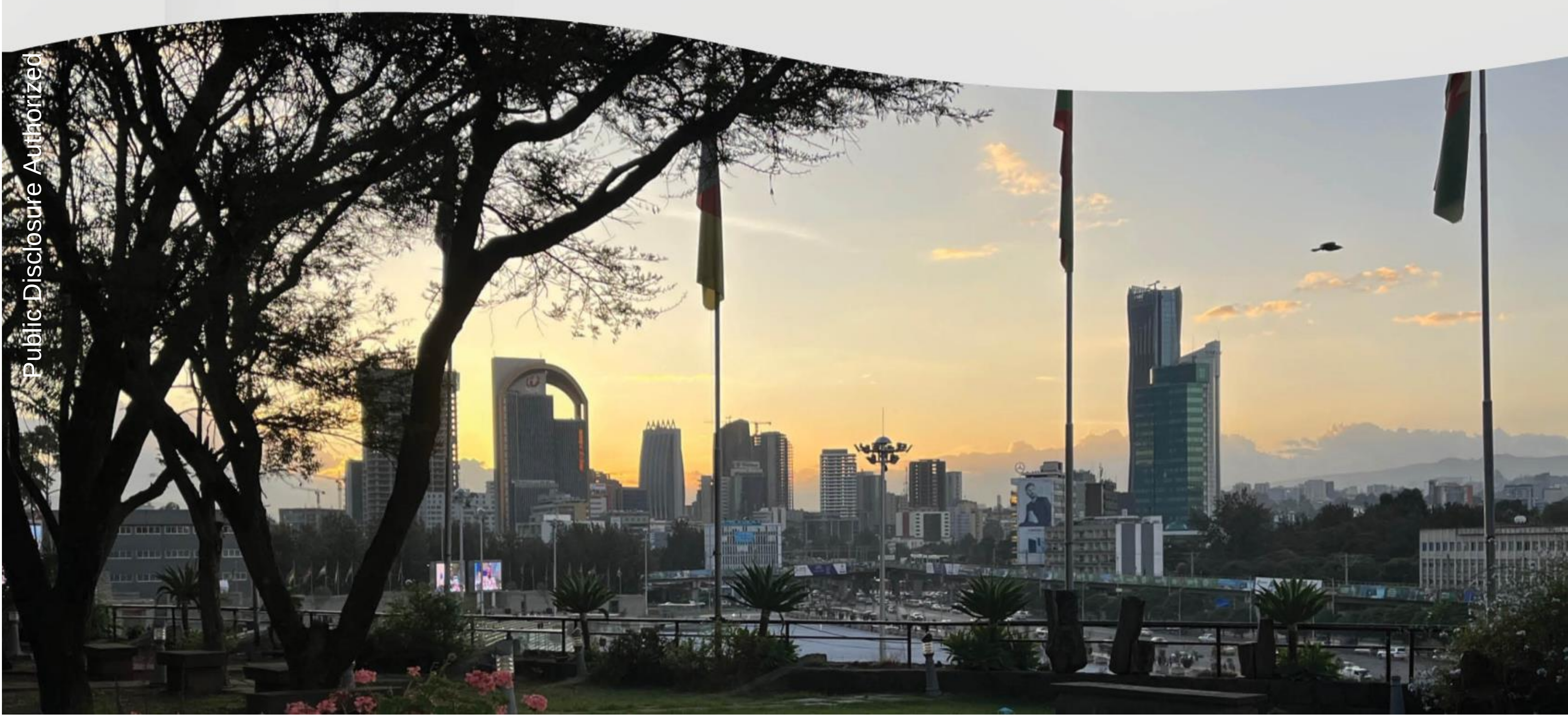

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Bending the Pollution Curve:

An Analysis and Prioritization of Pollution Management in Ethiopia

Jian Xie, Tamene Tiruneh, Bereket Belayhun Woldemeskel

with Christopher Arthur Lewis, Sven Schlumpberger, Lelia Croitoru, and Sarath Guttikunda

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ABBREVIATIONS AND ACRONYMS

AA	Addis Ababa
AASWMA	Addis Ababa Solid Waste Management Agency
ADB	Asian Development Bank
AQ	Air Quality
AQM	Air Quality Management
CH4	Methane gas
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CO_2e	Carbon dioxide equivalent
CRGE	Climate-Resilient Green Economy
EF	Emission Factor
EFCCC	Environment, Forest and Climate Change Commission
EPA	Environmental Protection Authority
EPGDC	Environment Protection and Green Development Commission
ETB	Ethiopian Birr
FTA	Federal Transport Authority, Ethiopia
GDP	Gross Domestic Product
GEOHealth	Global Environmental and Occupational Health
GHG	Greenhouse Gas
GIS	Geospatial Information Systems
LMIC	Low- and Middle-Income Countries
MoH	Ministry of Health
MSW	Municipal Solid Waste
MUDI	Ministry of Urban Development and Infrastructure
NO_2	Nitrogen Dioxide
NO_x	Nitrogen Oxides
O_3	Ozone
OECD	Organization for Economic Co-Operation and Development
PM_{10}	Particulate matter under 10 micro-meter diameter
$PM_{2.5}$	Particulate matter under 2.5 micro-meter diameter
ppm	Parts per million
PPP	Public-Private Partnership
PWC	Population Weighted Concentration
SO_2	Sulfur Dioxide
SSA	Sub-Saharan Africa
SW	Solid Waste
SWM	Solid Waste Management
UNEP	United Nations Environment Program
USD or US$	US Dollar
VOC	Volatile Organic Compounds
WASH	Water, sanitation, and hygiene
WHO	World Health Organization
WtE	Waste-to-Energy
$\mu g/m^3$	micro-grams per cubic meter

EXECUTIVE SUMMARY

Ethiopia has one of the fastest-growing economies in Africa, with an annual average GDP growth rate of 10 percent from 2005 to 2020. Its per capita income has increased from US$110 in 2003 to US$890 in 2020, and there has been significant progress in reducing poverty and improving access to services (World Bank, 2022a). Economic development in the country has been accompanied by population growth, urbanization, industrialization, and mobility. Cities and urban areas account for over 38 percent of the national GDP and 15 percent of the national workforce, and the urban population is expected to triple by 2034 (World Bank, 2015). Addis Ababa, Ethiopia's capital, is the most economically and politically significant city in the country. The population of Addis Ababa has increased at an annual average growth rate of 4.4% since 2015 and by 2020 had topped 4.8 million (United Nations, 2019). The city's GDP, at about ETB 90.9 billion, is some 8 percent of the national GDP and has grown over 15 percent annually on average in recent years (UN Habitat, 2017).

Ethiopia's economic growth has resulted in natural resource depletion, pollution problems, and environmental degradation, all of which threaten to slow or impede development gains. The cycle of economic growth, population growth, urbanization, and industrialization with inadequate environmental management in Ethiopia has corresponded with an increase in air, water, and solid waste pollution. For example, Addis Ababa's rapid urbanization presents many social and environmental risks including pollution (water, air, and noise), urban sprawl, solid and liquid waste management problems, illegal settlements, and loss of open green areas. Unmanaged urban sprawl and mobility in Addis Ababa have also exacerbated traffic congestion, pollution, land management, housing development, and social inclusion challenges. The city's groundwater resources are rapidly depleting, and water quality has deteriorated due to the improper disposal of wastewater, solid waste, and contaminants directly into rivers. Pollution has been impacting the environmental quality of airsheds, water bodies, land, and ecosystems, especially in major Ethiopian cities. It undermines the country's natural resource base; for example, water pollution has damaged aquatic diversity and productivity in rivers and lakes around Addis Ababa. Pollution also poses risks to health – such as the impact of air pollution on respiratory illnesses – and economic vitality, as health impacts harm productivity and human capital.

Pollution and environmental degradation often worsen as countries develop, industrialize, and require more natural resources, energy, and transportation. The Environmental Kuznets Curve (EKC) hypothesis suggests that, initially, economic growth increases pollution up to a certain income threshold, and then it begins to decrease pollution. Pollution reduction is not inevitable, however. Ethiopia must actively improve its pollution management practices and mitigate the impact of pollution on its economy, public health, and the natural environment as much as possible. With understanding and a public awareness of pollution problems, strong political will, and strong strategies for pollution management, Ethiopia may even bend the EKC and avoid the "pollute first, clean up later" development path that industrialized countries have taken—creating the chance for a cleaner environment, a healthier population, stronger economic growth, and accelerated development progress.

This study aims to identify, diagnose, and evaluate key urban pollution issues facing Ethiopia and advise governments on developing and prioritizing pollution management interventions through a long-term perspective. Based on their national significance, data availability, and the results of consultations with relevant government agencies, the cities of Addis Ababa, Bahir Dar, and Hawassa were selected as case-study cities for the analysis. The study assesses the socio-economic impacts of pollution problems in the selected study cities. It also estimates the costs of pollution, which are further used to prioritize pollution management issues in urban Ethiopia and provide an economic basis for recommended interventions and pollution management programs.

Addis Ababa and other Ethiopian cities are facing deteriorating air quality that undermines quality of life. An analysis of visibility data in Addis Ababa suggests that air quality has been declining for about 50 years, with the average air quality now approximately 1.6 times worse than it was in the 1970s (ASAP East Africa, 2019). $PM_{2.5}$ is considered the most relevant urban air quality indicator and an important risk factor for premature death worldwide (Cohen et al., 2005). According to air quality monitoring samples taken from Addis Ababa in recent years, mean daily $PM_{2.5}$ concentration far exceeded WHO guidelines for healthy air (Worku et al., 2020). For Addis Ababa, the population-weighted annual average of ambient $PM_{2.5}$ concentration was 30-36 $\mu g/m^3$ for 2016-2020 as compared with the WHO guideline of 5$\mu g/m^3$. Though the situation in secondary cities is less severe, air pollution is still a problem; annual concentrations for 2016-2019 were estimated at 20 $\mu g/m^3$ in Bahir Dar and 22 $\mu g/m^3$ in Hawassa, several times above the WHO threshold value. If no preventive actions are taken by the government, AQ in urban Ethiopia will deteriorate over the years.

There is a considerable health burden from air pollution. Using Global Burden of Disease methods, ambient $PM_{2.5}$ pollution is estimated to cause around 1,600 premature deaths each year in Addis Ababa, 90 in Bahir Dar, and 70 in Hawassa—along with an estimated 4,100 Years Lived with Disability in Addis Ababa and a proportional estimate in the secondary cities. As these figures represent only the effects of $PM_{2.5}$ pollution, they should be understood as only a fraction of the total impact of air pollution. In Addis Ababa, the main sources of air pollution are vehicle exhaust, residential activities, industry, and resuspended dust. In Hawassa, the main contributor to $PM_{2.5}$ pollution is residential activity, while wind dust is the main source in Bahir Dar.

Ethiopian cities exceed national or international standards on various dimensions of water quality, including biological, chemical, and heavy metal contamination. Industrial sources are a major contributor to water pollution, with 89% of wastewater volume in Addis Ababa, for instance, coming from the leather and footwear, food and beverage, and textile industries. Agricultural runoff, untreated sewage, improperly disposed solid waste, and non-point sources (such as stormwater runoff) are also sources of water pollution. These sources of pollution result in high levels of organic waste and bacteria in surface waters, eutrophication, heavy metal pollution, and ecological deterioration in the study cities. Evidence also suggests that surface water pollution leads to contamination of groundwater, which is the main source of drinking water in some study cities. Available data does indicate, however, that water bodies around Bahir Dar are less severely polluted than the Addis Ababa and Hawassa watersheds, though this does not mean that Bahir Dar does not also need intervention.

It is likely that residents of the study cities face substantial adverse effects from water pollution. Water pollution generates a variety of risks to human health, economic productivity, and ecosystem vitality. In Africa, it is estimated that water pollution, combined with inadequate sanitation, causes damages equivalent to 5% of GDP (Yohannes and Elias, 2017). Quantitative estimates of the health and other impacts of water pollution are not as readily available as those for air pollution, as the effects of water pollution are more diffuse. But studies in Addis Ababa (e.g., Abdhalah, 2016) indicate that around 25% of the population suffered from a solid waste or sanitation-related disease in 2008, and other research suggests a substantial burden of typhoid fever and diarrhea, diseases with probable links to water quality.

The study cities face a large solid waste pollution burden. In urban centers in developing countries of Africa, between 30% and 60% of municipal solid waste (MSW) goes uncollected. Ethiopia has few sanitary landfills, most of which are not properly managed. Most municipal solid waste is disposed of at open dumpsites, illegally littered or openly burned. Little SW is recycled. Solid waste in Ethiopian cities is generated largely by households, commercial entities, industries, and street sweeping. About 70% of solid waste is collected in Addis Ababa, and around 80% in Bahir Dar and Hawassa, indicating that large fractions of solid waste go uncollected in each study city, resulting in significant solid waste pollution. Recycling rates are low in Addis Ababa (4-5%), unreported for Bahir Dar, and more substantial in Hawassa (19%).

Direct results of solid waste pollution in Ethiopian cities include the proliferation of infectious disease via insects and rodents that congregate at waste sites, exposure to hazardous waste, and aesthetic impacts such as foul odor. The open burning of uncollected trash also contributes to air pollution. It is estimated that the solid waste sector produced 2.1 Mt CO_{2e} in 2020. Leaching from improperly managed landfills can also pollute soil, groundwater, and surface water bodies, and solid waste litter can clog drainage systems to contribute to flooding and water pollution. Addis Ababa also has a history of safety issues related to landfill management, most notably the 2017 explosion and landslide at the Reppie landfill, which resulted in over 100 fatalities. This picture suggests that there are important improvements to be made in both waste collection and disposal, and substantial room to increase recycling rates.

This study estimated the impact of pollution related to air, water, and solid waste at 3.6% of the GDP each year in Addis Ababa, 4.3% in Bahir Dar, and 5.5% in Hawassa (Figure ES1). The cost of air pollution is particularly worrying in Addis Ababa, due to a large population exposed to high levels of $PM_{2.5}$; meanwhile, solid waste mismanagement accounts for the largest cost in Bahir Dar and Hawassa, primarily because of the negative externalities related to inadequate landfill management (Table ES1). For all cities, air pollution costs were estimated based on the premature mortality and morbidity due to $PM_{2.5}$ exposure, which amounted to 0.8-1.3% of GDP in the study cities. Water pollution costs—the health impacts from inadequate water, sanitation, and hygiene (WASH) practices and from wastewater irrigation, residents' willingness to pay for improved municipal wastewater treatment, and damage to fish catch in surrounding freshwater bodies—amount to about 0.6-1.1% of GDP, though this is likely a significant underestimate. Finally, the solid waste pollution costs—reflected through the loss of property value near landfills, loss of recyclable material, and residents' willingness to pay for improved collection—attain 1.2-4.0% of GDP. As the first-time effort to estimate the impacts of pollution in the three cities, these results should be regarded as **order-of-magnitude** estimates, aimed to help assess and compare the costs and benefits across environmental media and prioritize prospective pollution management programs and interventions.

Figure ES 1. Estimated pollution cost by city (% of the city's GDP, 2019)

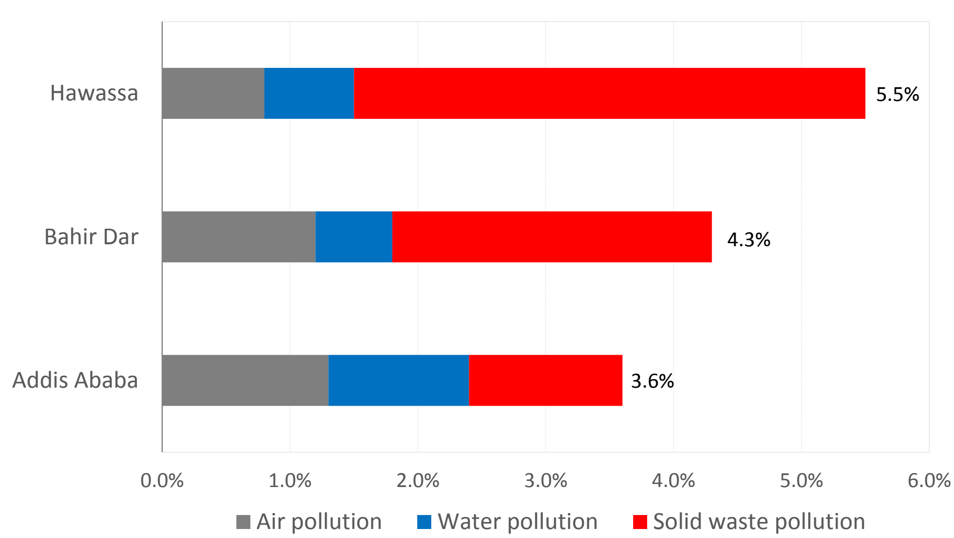

Table ES 1. Estimated pollution costs (US$ million, 2019)

	Addis Ababa	Bahir Dar	Hawassa
Air pollution	78	4.5	3.4
Water pollution	66.6	2.5	2.8
Solid waste pollution	73.2	9.8	15.9
Total	**217.8**	**16.8**	**22.1**

The study concludes that all three forms of pollution impose and deserve equal attention and priority in pollution management. Each form of pollution requires a different set of management measures. Solid waste pollution can be addressed with improvement of solid waste collection and disposal. Solid waste separation and recycling also has potential win-win impacts, since it diverts waste from the stream bound for landfill and generates a resource that can be sold on the market. The potential for composting of organic waste is another profitable resource that can potentially be generated through improved collection and sorting. Water pollution can be improved by increasing wastewater collection and treatment. The health impact of water pollution can be reduced by improving water supply standards and human hygiene to cut the link between polluted water sources and humans. Air pollution is the most difficult to address since it involves multiple sectors and numerous stakeholders. It is necessary to control air pollution but could be more costly and difficult to mobilize all parties to control air pollution emissions from various sources.

To begin intensifying pollution control efforts, authorities should focus on strengthening institutions, as well as consider highest-priority strategies for each pollution media. Improvements to institutional arrangements include establishing a clear and stable organizational structure to clarify agency roles and responsibilities; strengthening coordination between regulatory stakeholders; ensuring that agencies tasked with pollution management have sufficient staff and capacity; involving the public in pollution control efforts; and streamlining data collection, access to information, and knowledge management.

Control of air pollution requires regulatory and policy action, budgeting and capacity building, air quality monitoring, and further analytical work. The Ethiopian government has begun to take various actions, including shifting from the use of fossil fuels to renewable energy in the transport and other sectors, to address the above-mentioned problems and related issues. The government is also striving to reduce households' dependence on biomass-based fuel (firewood and charcoal) by promoting the use of cleaner cooking technologies as per the goals of the GTP-2 and the CRGE Strategy. Recommendations for further action in each area of air pollution control are provided in a recent World Bank study on AQM in Ethiopia (Xie et al., 2021).

Several measures have the potential to quickly improve water quality in the study cities. Sources of water pollution were grouped in three categories, each of which have some priority areas. First, point sources of pollution, specifically from industries and commercial activities, should be tackled, for which authorities should aim to step up enforcement of existing regulations and examine areas to increase regulatory efficacy. Second, addressing water contamination from landfills and solid waste disposal sites should also be a priority, in addition to better understanding the hazard from unregulated solid and hazardous waste disposal. Lastly, the remaining non-point sources should be addressed in parallel with the other two categories with priority given to improvements in sanitation (starting with ending open defecation) and measures to prevent agricultural run-off. In addition to addressing the sources of pollution, it is important to strengthen water resource management, water quality monitoring, investment in high-quality distribution networks, and environmental enforcement. Creating dedicated authorities to ensure adequate resource management, monitoring, and enforcement would further assist in water quality improvements, since the collected data can be used as a basis for further pollution reduction regulations and interventions.

Priority areas of intervention in solid waste management (SWM) include technical support, infrastructure investment, public awareness building, and inclusion. The study cities should provide adequate technical expertise and training to the staff and operators of transfer and sorting stations to reduce the occurrence of improper waste disposal as well as improve the areas' overall cleanliness and safety. Physical improvements to SWM infrastructure should focus on collection, recycling, sanitary landfills, and safe closure and rehabilitation of old dumpsites. Public participation takes on particular importance in the management of solid waste. In particular, household participation in waste separation at the source is vital for enhancing recycling and composting practices. Local authorities in Ethiopia will also need to assess the feasibility of private sector participation and try to attract private investment. Lastly, the planning and development of integrated SWM systems should also address informal recyclers, whose livelihoods rely on waste picking and recycling activities and whose work should be recognized through formalization.

ACKNOWLEDGMENTS

This report is the final output of the World Bank's Advisory Services & Analytics program (ASA) entitled "Ethiopia: Pollution Management." Launched in July 2021, the ASA aims to diagnose, valuate, and prioritize key urban pollution issues facing Ethiopia, particularly in Addis Ababa and other cities selected for the analysis, and assist the governments in developing and prioritizing pollution management programs in a long-term perspective. The program was developed under the general guidance of Ousmane Dione (Country Director for Ethiopia), Doina Petrescu (Operations Manager for Ethiopia), and Iain Shuker (Practice Manager, Environment, Natural Resources and Blue Economy (ENB) Global Practice) at the World Bank.

This report was prepared by Jian Xie, Tamene Tiruneh, and Bereket Belayhun Woldemeskel, with Christopher Arthur Lewis, Sven Schlumpberger, Lelia Croitoru, and Sarath Guttikunda. Kimberly Worsham helped conduct a literature review. Other team members who were involved in the development and implementation of the ASA include Dinkneh Tefera (Urban Development Specialist); Tamru Demsis Temam (Sr. Environmental Specialist), Wendwosen Feleke (Operations Officer), and Wenyu Jia (Sr. Urban Transport Specialist).

The report benefits from the participation and support of government officials and experts from various Ethiopian government agencies and institutions, particularly the Federal Environmental Protection Authority (FEPA), Ministry of Urban Development and Infrastructure, Ministry of Water and Energy, Ministry of Transport (MoT), Federal Transport Authority (FTA), and Addis Ababa Environmental Protection Authority (AAEPA). In particular, the World Bank team would like to express their appreciation to Girma Gemechu (Director General, Compliance Monitoring and Enforcement Directorate, FEPA), Yoseph Kebede (Environmental Management Specialist, Project Implementing Unit, MUDI), Semunesh Golla (Director of Water Quality and Hydrology, MoWE), and Fantu Kifle (Climate change team leader, Addis Ababa EPA) for their support and active participation in the ASA activities. The report also benefits from discussions and consultations with representatives and experts from a group of international organizations actively working on pollution management in Addis Ababa, such as UN-Habitat, C40 Cities, UNEP, U.S. Embassy in Addis Ababa, and U.S. EPA.

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Chapter 1 Introduction

Ethiopia had one of the fastest-growing economies in Africa, with an annual average GDP growth rate of 10 percent from 2005 to 2020. Despite the COVID-19 pandemic, the country remains the fastest growing economy in the region, with 6.1 percent growth in FY2019/20 (World Bank, 2021). As of 2020, Ethiopia was the second most populous nation in Africa, with a population of 115 million. Its per capita income has increased from US$110 in 2003 to US$890 in 2020, and there has been significant progress in reducing poverty and improving access to services (World Bank, 2022a).

Ethiopia's economic development has been accompanied by population growth, urbanization, industrialization, and mobility. Urbanization is important for Ethiopia's growth, as cities and urban areas account for over 38 percent of the national GDP and 15 percent of the national workforce, according to a World Bank study (World Bank, 2015). The study estimates the rate of urbanization at 5.4 percent a year – which would triple the urban population by 2034. Addis Ababa, Ethiopia's capital, is the most economically and politically significant city in the country. The population of Addis Ababa has increased at an annual average growth rate of 4.4% since 2015 and by 2020 had topped 4.8 million (United Nations, 2019). The city's GDP, at about ETB 90.9 billion, is some 8 percent of the national GDP and has grown over 15 percent on average in recent years (UN Habitat, 2017). Industrialization has been a national strategy of Ethiopia, playing an important role as a springboard for economic development. Rapid economic development and urban expansion have drastically increased the demand for motorization. For example, the number of registered vehicles in Addis Ababa increased by 40% between 2016 and 2020.

Ethiopia's economic growth has also resulted in natural resource depletion, pollution problems, and environmental degradation which threaten to slow or impede development gains. The cycle of economic growth, population growth, urbanization, and industrialization with inadequate environmental management in Ethiopia has corresponded with an increase in air, water, and solid waste pollution. For example, Addis Ababa's rapid urbanization presents many social and environmental risks, including pollution (water, air, and noise), urban sprawl, solid and liquid waste management problems, illegal settlements, and loss of open green areas. Unmanaged urban sprawl and mobility in Addis Ababa have also exacerbated traffic congestion, pollution, land management, housing development, and social inclusion challenges. The city's groundwater resources are rapidly depleting, and water quality has deteriorated due to the improper disposal of wastewater, solid waste, and contaminants directly into rivers. Pollution has been impacting the environmental quality of airsheds, water bodies, land, and ecosystems, especially in major Ethiopian cities. It undermines the country's natural resource base; for example, water pollution has damaged aquatic diversity and productivity in rivers and lakes around Addis Ababa. Pollution also poses risks to health – such as the impact of air pollution on respiratory illnesses – and economic vitality, as health impacts harm productivity and human capital.

Sustainable development demands the integrated environmental management of all sources of pollution and environmental pressures. Air, water, and solid waste pollution are part of an interlinked system that negatively affects environmental quality, public health, and living standards. While the proximate causes of each form of pollution may differ, they are driven by shared underlying factors: economic, demographic, and governance. They also exhibit causal links and cascading impacts. For instance, poor solid waste management can lead to waste entering rivers and damaging water quality, or waste being burned and causing air pollution. Pollution management requires an integrated and inclusive approach to effectively manage complex pollution problems in all environmental media.

The Government of Ethiopia (GoE) has demonstrated political will and a commitment to environmental management, introducing a set of environmental policies and strategies as well as establishing the required regulatory institutions. Given the increasing understanding of the importance of pollution management, the GoE has begun to set goals for environmental protection. Ethiopia's Climate Resilience and Green Economy (CRGE) strategy fully acknowledges the challenges of pollution management and suggests levers of pollution reduction. The GoE's National Environmental Law Development and Enforcement Programme (NELDEP) from 2020 to 2030 identifies air pollution as a key area for improvement in its vision for integrating environmental laws into Ethiopia's development strategy (Government of Ethiopia, 2020). Additionally, Ethiopia's Growth and Transformation Plans (GTP I &II) dedicate a specific pillar to properly managing rapid urbanization. Also crucial to post-pandemic green recovery efforts is improving air quality, water pollution, and solid waste management. The government recognizes that long-term economic growth must incorporate sustainable, climate-aligned development to combat pollution challenges. At the city level, Addis Ababa has recently developed its air quality management plan and solid waste management strategy.

However, gaps in institutional capacity, coordination, technical and financial resources, and information pose barriers to integrated pollution management in the country. The weak capacity of and poor coordination between stakeholders, lack of technical expertise and funding, inadequate policy knowledge, absence of enforcement strategies, unavailability of appropriate working guidelines, and disconnected institutional setups all lead to gaps in the implementation of environmental policies. An integrated approach to pollution management is necessary to work across sectors and engage a diverse set of public and private stakeholders. For instance, Ethiopia needs to establish a national air quality monitoring system and deepen its analytical work to better inform AQM. And because of their contributions to growing ambient air pollution emissions, it is important to prioritize and implement air pollution control measures from all polluting sectors.

Policy and institutional changes are necessary to strengthen environmental management and improve environmental quality in Ethiopia. While national and local governments have recently developed some environmental management strategies – for example, Addis Ababa's recent approval of the city's first air quality management (AQM) plan – the country needs to strengthen its institutional arrangements for environmental management. The government should prioritize strengthening the policy framework for implementing environmental management strategies and plans.

Prioritizing pollution management issues will help Ethiopia to better program its pollution management efforts. As Ethiopia is facing growing pollution problems in the years to come and has limited capacity for pollution management, it is important for governments at the national and local level to assess pollution problems and their impacts, and effectively utilize limited capacity and resources to generate tangible results on key issues.

The report summarizes the findings of the Ethiopia pollution management study conducted by the World Bank. It aims to identify, diagnose, and evaluate key urban pollution issues facing Ethiopia and advise governments on developing and prioritizing pollution management interventions through a long-term perspective. Based on data availability and consultation with relevant government agencies, the cities of Addis Ababa, Bahir Dar, and Hawassa were selected as case study cities for the analysis. The study assesses the socio-economic impacts of pollution problems in the selected study cities. It also estimates the costs of pollution, which are further used to prioritize pollution management issues in urban Ethiopia and provide an economic basis for recommended interventions and pollution management programs. Box 1 provides a socioeconomic description of the three cities.

Box 1. The Socioeconomics of the Three Selected Study Cities

Addis Ababa: Addis Ababa, Ethiopia's capital, is the most economically and politically significant city in the country. The population of Addis Ababa has increased since 2015 at an annual average growth rate of 4.4% and in 2020 reached over 4.8 million. The city has a subtropical highland climate and covers an area of around 527 square kilometers, surrounded primarily by cropland. It is less densely populated than many other major Sub-Saharan African cities. Addis Ababa is administered both as a federal capital and an autonomous jurisdiction equivalent to other Ethiopian states. It consists of 11 sub-cities, further divided into 117 smaller administrative districts.

The city's GDP, at about US$6.1 billion in 2019, grew on average by over 10 percent annually from 2000 to 2015. Most city residents are employed in either the consumer service sector or industry and construction; but the greatest share of the city's gross economic value comes from financial and business services. Pollution challenges are substantial. A recent study conducted by the World Bank estimated around 1,600 premature adult deaths from outdoor $PM_{2.5}$[1] exposure in Addis Ababa. Only an estimated 70% of solid waste is collected. And water pollution is also a significant problem: With only around 16% of the city connected to the sewerage system, human feces end up in rivers. Due to these issues, an integrated approach to pollution management offers the prospect of improved quality of life and enhanced development in Addis Ababa.

Bahir Dar: Bahir Dar, population 375,000, is the capital of Amhara Regional State. It has a warm and temperate climate and, as the origin of the Blue Nile or Abbay River, is also one of the leading tourist destinations in the country. In 2002, it was awarded the UNESCO Cities for Peace prize for addressing the challenges of rapid urbanization. Bahir Dar has developed rapidly as a regional metropolitan hub and resort city, with continuous construction of hotels and housing to accommodate the rising numbers of tourists and residents. The city's GDP was an estimated $390 million in 2019. Other emerging sectors include construction, textiles, agro-processing, tanning, and plastics. Pollution management challenges have developed as the city has grown. About 20% of municipal solid waste is uncollected. The Lake Tana basin appears to be less impacted by water pollution than water bodies in other study cities, but still faces challenges from industrial wastewater, urban runoff, sewage, and agricultural runoff.

Hawassa: Hawassa is located on the shores of Lake Hawassa in the Great Rift Valley. The city is the capital of both the Sidama and the Southern Nations, Nationalities, and People's regions, and has a population of 387,087. It is among Ethiopia's leading cities in terms of population growth, economic development, and tourism. The city's GDP was an estimated $400 million in 2019.[2] The country's first large-scale industrial park was established in Hawassa in 2016. Other urban development projects are expected to increase the rate of urban growth. The main economic activities in Hawassa are agro-processing industries, tourism and leisure industries, education and, until recently, the garment and textile industry of the industrial park. Hawassa faces similar pollution challenges to other Ethiopian cities. The existing open dump site is incompatible with the nearby residential settlements, and 20% of solid waste

[1] $PM_{2.5}$ refers to fine inhalable particles, with diameters that are generally 2.5 micrometers and smaller, that can be inhaled into the lungs and even enter the bloodstream.

[2] GDP figures for Bahir Dar and Hawassa are coarse estimates derived from publicly available nighttime luminosity data, based on the relationship between luminosity and GDP described by Beyer et al. (2018) and Henderson et al. (2012).

is left uncollected. Hawassa, however, is notable among Ethiopian cities for its comparatively high recycling rate — 19% according to a 2017 study. Lake Hawassa and other water bodies are faced with pollution from untreated industrial wastewater, urban runoff, sewage, and agricultural runoff. As a result, several measures of water pollution in Lake Hawassa exceed international and Ethiopian pollution standards.

This report focuses on the environmental problems of air and water pollution and solid waste in the study cities. It does not encompass all pollution issues faced in Ethiopian cities. This research is part of ongoing World Bank engagement on pollution issues in Ethiopia and it builds on previous work conducted on managing air quality (Xie et al., 2021) and solid waste (Xie and Mito, 2021) in Addis Ababa. With regards to air pollution, the study only covers ambient air pollution. Indoor air pollution, another major problem, is introduced through a literature review of available research. A number of pollution issues, such as hazardous waste and land contamination, are only briefly mentioned. Light and noise pollution are not included in the analysis due to limited available resources, time, and information. They deserve careful analysis in future follow-up studies.

The analysis of pollution management in this report adopts a range of qualitative and quantitative methods, including information collection, a review of the literature and government documents, stakeholder consultation, environmental and health impact assessment, and economic valuation. One of the main limitations the current study faced was the availability of reliable data — such as monitored ambient air quality data and surveyed solid waste generation data — which limited quantitative assessment and economic valuation. Wherever possible, literature reviews and consultation with local stakeholders were used to select the best available data for the analysis. In the health impact assessment and economic valuation, conservative valuation techniques and assumptions were made to estimate low-end values. In addition, the COVID-19 pandemic impacted normal stakeholder interactions. While efforts were made to validate data wherever possible (for example, solid waste data in study cities), there are obvious weaknesses in some data, which had to be derived from assumptions.

This work is aimed at providing a high-level analysis of the pollution situation in Ethiopian cities, rather than a comprehensive evaluation of any specific pollution problem or intervention. Accordingly, the economic valuation of pollution costs conducted in this research should be considered a preliminary estimate of lower-bound values. This study did not conduct the detailed analysis—including cost-benefit analysis—necessary to evaluate and prioritize specific pollution control investments. Further verification and cross-checking of data would also be necessary in future studies and action plans for specific pollution management interventions.

The report is structured as follows. Chapter 2 introduces the basics of pollution problems and environmental impacts as well as the relationship between economic growth and pollution intensity. It then discusses the growing trend of pollution in Ethiopia and the country's institutional arrangement for pollution management. Chapters 3-5 analyze the problems of air pollution, water pollution, and solid waste, respectively, in the three study cities. The costs of pollution for each environmental medium in the three cities are estimated in Chapter 6. Chapter 7 prioritizes pollution management issues and provides recommendations for Ethiopia.

Chapter 2 Pollution Management: Concepts, Global Trends, and National Context

2.1 Basics of pollution and pollution impacts

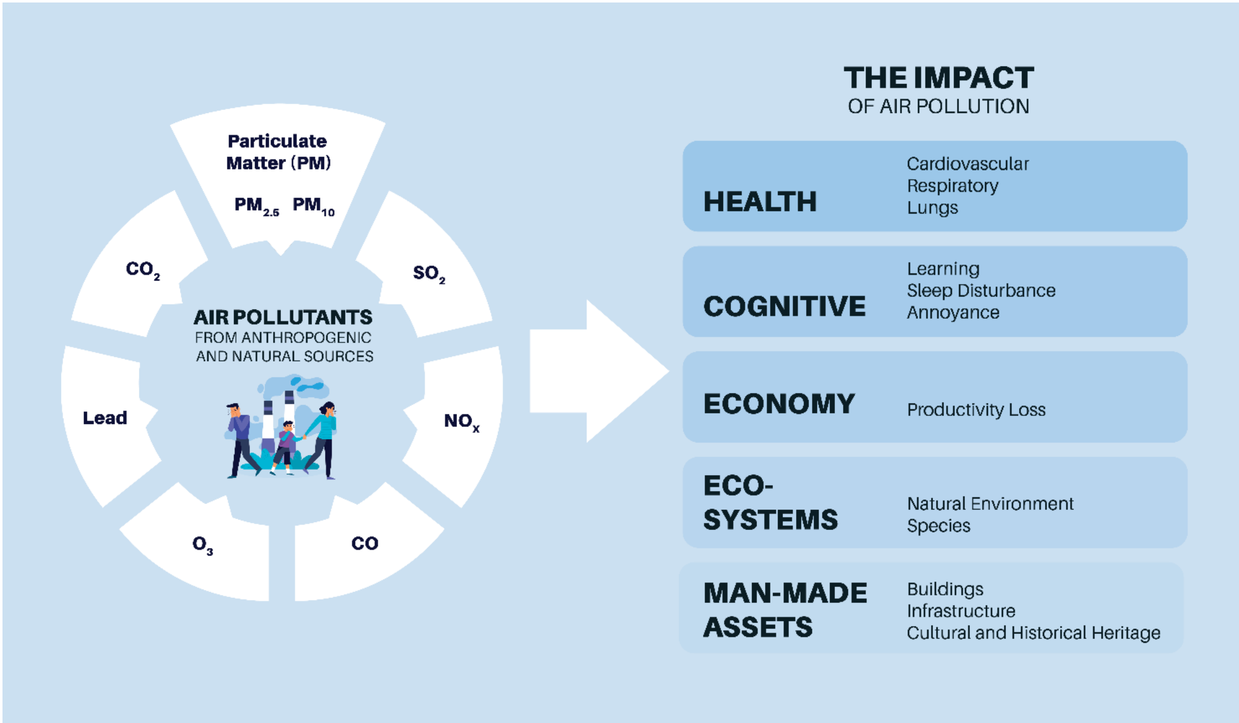
Pollution is defined as the introduction of harmful materials into the environment, including air, water, and land. Pollutants can be natural or generated from human activities, such as power generation, industrial production, motorized vehicles, households, and other entities or infrastructure. Many aspects of economic development can lead to pollution, such as air pollution from motor vehicle exhaust or coal-fired power, sewage and solid waste pollution from homes and businesses, or water pollution from agricultural chemicals (National Geographic).

Pollution sources are typically classified as point or non-point. The U.S. Environmental Protection Agency defines point source pollution as "any single identifiable source of pollution from which pollutants are discharged, such as a pipe, ditch, ship or factory smokestack" (U.S. EPA). Power plants, factories, sewage treatment plants, and open dumpsites are common types of point sources. All other sources of pollution are considered "non-point" sources (NPS), which typically come from diffuse origin points, like land runoff, precipitation, atmospheric deposition, drainage, seepage, or hydrologic modification. According to the U.S EPA, NPS water pollution is driven by the movement of precipitation or snowmelt, which picks up pollutants and carries them into water bodies. Air pollution can also be further classified as mobile sources in origin, such as from vehicles like cars, planes, and trains, stationary sources, like factories, or area sources, such as agricultural lands or cities (U.S. EPA, 2016).

Pollution does a wide set of damage to the natural environment, biodiversity, human health, human society, and local and global economies, and different types of pollutants and their level of intensity may generate different impacts. For instance, particulate matter (PM) is a complex pollutant further classified by its aerodynamic diameter in micrometers (μm). $PM_{2.5}$, with a diameter less than or equal to a nominal 2.5μm, can pass the barriers of the lungs, enter the bloodstream, and destroy the integrity of the blood-brain barrier, thus causing premature deaths, as well as respiratory, cardiovascular, and neurological diseases (Peeples, 2020; Bowe et al., 2019; Shou et al., 2019; Brook et al., 2010). Figure 1 illustrates the impacts of air pollution.

Pollution and its impacts are further driven by various factors that add pressure on the environment and economy, causing socio-economic impacts that require policy responses. Figure 2 illustrates the drivers, pressures, state, impact, and response (DPSIR) framework for pollution management.

Figure 1. Air Pollution and Its Impacts



Source: Xie, et al., 2021.

Figure 2. DPSIR framework for Pollution Management

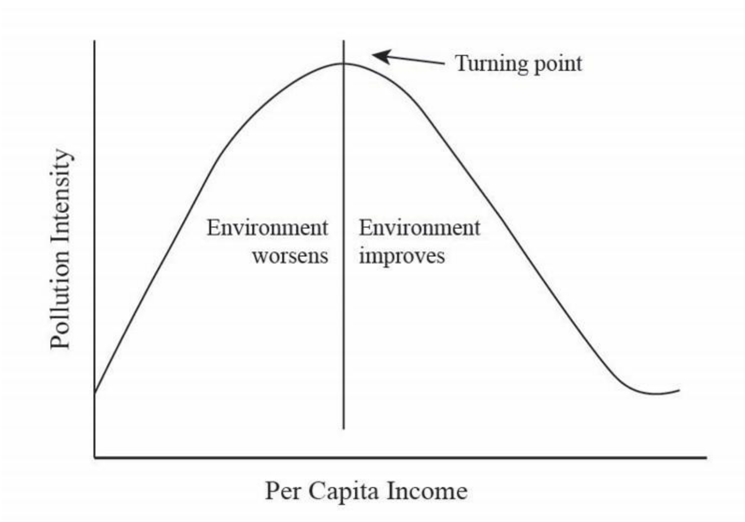
2.2 Development and pollution

Pollution has been a problem for a long time. Increasing human population and economic activity, especially since industrialization, have significantly increased pollution and its environmental impacts.

Development (or economic growth) and pollution (or environmental quality) are closely related because they share similar economic and environmental systems. While their relationship can be complex, there is a consensus that connections exist between them (Ali & De Oliveira, 2018; Egbetokun et al., 2018). As a result, efforts have been made to understand how development and the environment interact. Ideally, economic growth and prosperity should help ensure sustainability and a safe environment. However, in practice this does not necessarily occur. More often, pollution and environmental degradation worsen as countries develop, industrialize, and require more natural resources, energy, and transportation—resulting in more air, water, and solid waste pollution. An understanding of how development and pollution influence each other can provide insight into which pollution management strategies are most appropriate for the Ethiopian development context.

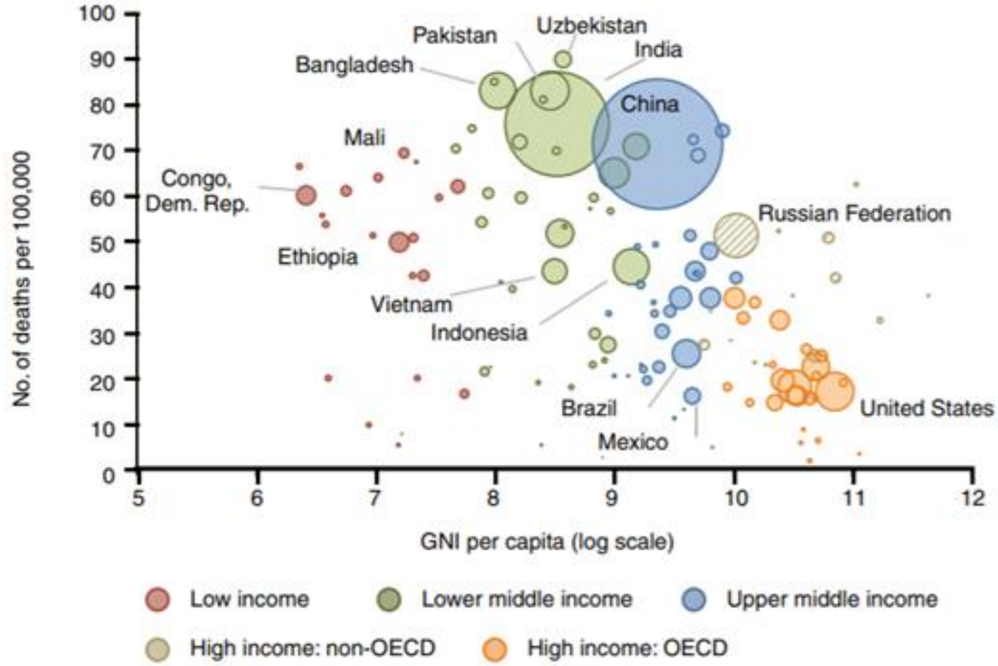
In recent decades, researchers have tried to understand the relationship between growth and pollution. They got a different understanding of the relationship and believe that pollution intensity may take different paths along with economic growth, such as an increase, decrease, or change over the years depending on certain economic thresholds. However, a simple inverted U-shaped curve, called the Environmental Kuznets Curve (EKC), has received much attention and exploration. The EKC, as shown in Figure 3 below, indicates that, initially, economic growth increases pollution up to a certain income threshold, when economic growth then begins to decrease pollution.

Figure 3. Illustrative Environmental Kuznets Curve



The EKC concept was introduced in 1991 based on carbon dioxide emissions (Zaied et al., 2017; Thompson, 2012; Orubu & Omotor, 2011; Grossman & Krueger, 1991). There has also been evidence suggesting that the EKC may apply to particulate matter (Orubu & Omotor, 2011). Figure 4 below further shows the relationship between environmental impacts (represented by death rates from $PM_{2.5}$ pollution) versus the gross national income (GNI) per capita of various countries in 2013. This real-world data illustrates that economic growth in low-income and some middle-income countries may cause an increase in death rates. For high-income and some middle-income countries, the trend reverses.

Figure 4. Household $PM_{2.5}$ death rate versus gross national income (GNI) per capita in 2013



Note: Size of the bubble references the total number of deaths of each country.

Source: World Bank and IHME, 2016

Many proponents of the EKC argue that it's a good starting point for understanding the relationship between economic growth and pollution (Karsch, 2019; Thompson, 2012). Some studies, however, argue that the EKC concept has oversimplified the real, complex relationship between economic development and the environment, as income could be only one of several factors that impact environmental health, such as education, corruption, and regulation (Jayachandran, 2021; Egbetokun et al., 2019; Stern, 2017; Orubu & Omotor, 2011).

Many studies test how EKC applies to different pollutants and geographic settings (Karsch, 2019; Boopen & Vinesh, 2016; Orubu & Omotor, 2011). Table 1 below summarizes the results of some EKC studies in different countries. While many studies substantiated the EKC, overall results are mixed.

Table 1. Compilation of Major Studies for EKC

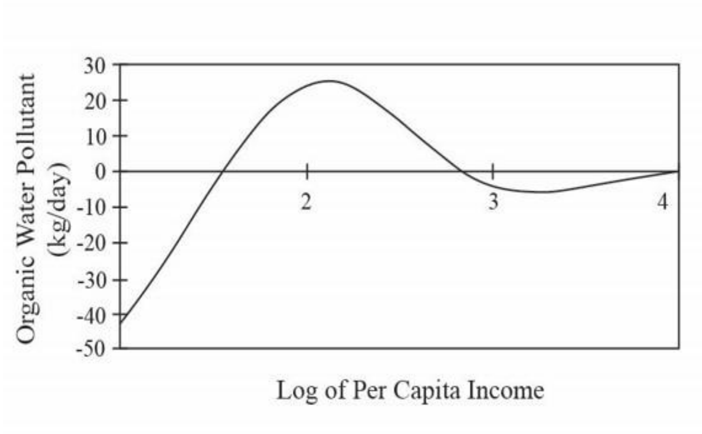
AUTHORS	REGION	PERIOD	POLLUTANT	CONCLUSION
MOOMAW & UNHRUH, 1997	16 countries	1950-1992	CO_2	No EKC relationships
DE BRUYN ET AL., 1998	Netherlands, UK, USA, Germany	1960-1993	CO_2, NOx, SO_2	No inverted U-shaped curve
AGRAS & CHAPMAN, 1999	34 countries	1971-1989	CO_2	Confirmed inverted U-shaped curve

AUTHORS	REGION	PERIOD	POLLUTANT	CONCLUSION
DIJKGRAAF & VOLLEBERGH, 2001	OECD countries	1960-1997	CO_2	Many countries do not have an EKC pattern
LUCENA, 2005	Brazil	N/A	CO_2	Confirmed EKC relationship
ARRAES ET AL., 2006	Several countries	1980, 1985, 1990, 1995, 2000	CO_2	Confirmed inverted U-shaped curve
AHMED & LONG, 2012	Pakistan	1971-2008	CO_2	Confirmed inverted U-shaped curve
BORHAN & AHMED, 2012	Malaysia	1996-2006	BOD, Cd, As	Confirmed EKC relationship for BOD
BORHAN ET AL., 2012	Asean 8	1965-2010	CO	Confirmed EKC relationship
ESTEVE & TAMARIT, 2012	Spain	1857-2007	CO_2	Confirmed EKC relationship
FOCACCI, 2005	Brazil, China India	1975-1997 1970-1997	CO_2	No EKC relationship
KUMNAS & MYLLYNTAUS, 2010	Finland	1950-2001	SO_2	Confirmed inverted U-shaped curve
LIPFORD, 2010	G8-5 countries	1950-2004	CO_2	Found N-shaped curve
MARTINEZ-ZARZOSO & BANGOCHEA-MORANCHO, 2004	22 OECD countries	1975-1998		Found N-shaped curve
SONG ET AL., 2008	China	1985-2005	Waste gas emissions	Confirmed inverted U-shaped curve

Source: Compiled and adapted from Boopen & Vinesh, 2016; Inglesi-Lotz & Bohlmann, 2014.

Some EKC studies have further found that many higher-income countries adhere to more of an N-shaped curve (Figure 5). This means there could be another turning point after which economic growth increases certain forms of pollution again (Karsch, 2019; Egbetokun et al., 2018; Boopen & Vinesh, 2016; Orubu & Omotor, 2011). Furthermore, studies assessing different pollutants have shown that the EKC hypothesis only applies to a few pollutants, making it difficult to rely on it for understanding the larger environmental implications (Egbetokun et al., 2018; Inglesi-Lotz & Bohlmann, 2014). Another challenge with the EKC has been the unclear threshold in per capita income needed before economic growth starts to reduce pollution. Some studies have found the turning point differs based on pollutant and location.

Figure 5. EKC Study Indicating an N-shaped Curve



Source: Orubu & Omotor, 2011.

Low-income countries in the early stages of industrialization, with rapid population growth and urbanization, typically face dramatic increases in pollution, risking environmental degradation. This is particularly true in most countries in Sub-Saharan Africa, where increasing air and water pollution and solid waste have been widely observed in most African cities, including Addis Ababa, Kampala, Lagos, and Nairobi. While some EKCs for CO_2, particulate matter, and other potential pollutants have been found in relatively wealthy Northern African countries, SSA has few quantitative studies that can validate an EKC relationship. The increasing pollution trend in SSA may also be strongly related to other variables, such as rapid population growth, political instability, governance, and education level. There has not been an economic threshold found that can serve as a turning point (Boopen & Vinesh, 2016). Only studies on South Africa have shown an inverted U-shaped curve (at US$493 per capita) for particulate matter and an N-shaped curve (with turning points between US$5,120 and US$7,813) for CO_2 and N_2O (Orubu & Omotor, 2011; Egbetokun et al., 2018).

In sum, most African countries are on a rising trajectory of pollution as their economies, populations, and industrial sectors grow. While the validity and dynamics of the EKC are not fully understood, there is evidence that policy and investment measures are capable of bending the curve. Dasgupta et al. (2004) argue that the EKC framework does not account for evidence that strong environmental governance can address pollution, even in developing countries. If the impact of governance and geographic vulnerability is taken into consideration, the link between pollution and income becomes weaker. The authors also suggest that the EKC can be mitigated by focusing economic activity in cities whose geography makes them less susceptible to air pollution. Furthermore, even if an EKC relationship exists, the height and shape of the curve may be influenced by factors such as economic structure, development strategy, and regulation (He and Wang, 2011).

This evidence suggests that countries, including Ethiopia, must actively improve their pollution management practices and mitigate the impact of pollution on economies, public health, and the natural environment as much as possible. With understanding and a public awareness of pollution problems, strong political will, and strong strategies for pollution management, Ethiopia can act ahead of the curve. With the right interventions, Ethiopia may even bend the EKC and avoid the “pollute first, clean up later” development path that industrialized countries have taken—creating the chance for a cleaner environment, a healthier population, stronger economic growth, and accelerated development progress.

2.3 Increasing pollution in Ethiopia

As the sections above describe, economic development in Ethiopia has been accompanied by increasing pollution and environmental deterioration driven by population growth, urbanization, industrialization, and mobilization. The current stage of development has corresponded with an increase in air, water, and solid waste pollution in Addis Ababa and other Ethiopian cities. The population of Addis Ababa was 2.3 million in 2000 and was expected to reach 5 million by 2021. During the same timeframe, its urban area increased dramatically. Unmanaged urban sprawl in Addis Ababa has also exacerbated traffic congestion, pollution, land management, housing development, and social inclusion challenges. The improper disposal of wastewater, solid waste, and contaminants directly into rivers has deteriorated water quality. Now pollution in the city poses a variety of risks to public health. Pollution also harms economic vitality, as health impacts harm productivity and human capital. And it also undermines the country's natural resource base. For example, water pollution has damaged aquatic diversity in rivers and lakes around Addis Ababa.

Addis Ababa and other Ethiopian cities are facing deteriorating air quality that undermines quality of life. An analysis of visibility data in Addis Ababa suggests that air quality has been declining for about 50 years, with the average air quality now approximately 1.6 times worse than it was in the 1970s (ASAP East Africa, 2019). $PM_{2.5}$ is considered the most relevant urban air quality indicator and an important risk factor for premature death worldwide (Cohen et al., 2005). In 90 percent of samples taken from Addis Ababa in 2015 and 2016, mean daily $PM_{2.5}$ concentration exceeded WHO guidelines for healthy air (Worku et al., 2020). An air pollution source apportionment study shows that contributions to $PM_{2.5}$ pollution in Addis Ababa are dominated by vehicle exhaust, residential activities, and resuspended dust. It also finds that industrial and transport air pollution continue to grow. The transport sector – including urban transport, aviation, and roads – generates 29% of $PM_{2.5}$ and over 90% of CO_2. Its contribution to ambient $PM_{2.5}$ concentration is even greater, reaching 35%.

There is a considerable health burden from air pollution. Due to poor air quality, residents of Addis Ababa are at considerable risk of heart and lung diseases and premature death. However, improving air quality management and reducing pollution would prevent illnesses, save lives, and lower health costs. A recent study conducted by the World Bank estimated around 1,600 premature adult deaths each year from outdoor $PM_{2.5}$ exposure in Addis Ababa (Xie et al., 2021). The total health cost of air pollution in Addis Ababa is estimated at $78 million and is equivalent to about 1.3% of the city's GDP. Poor air quality also jeopardizes COVID-19 pandemic control efforts since air pollution may intensify the effects of coronavirus infection.

Water quality issues are also driven by unplanned urbanization, poor waste management practices, and inadequate sanitation infrastructure. Water pollution is pervasive in water bodies, especially in the urban segments of rivers. An assessment of the ecological status of four large Ethiopian river basins (the Awash, Nile, Omo-Gibe, and Tekeze River basins) indicated that there is considerable urban water quality deterioration in all four basins (Awoke et al., 2016). Most pollutants result from non-point sources, including runoff from agricultural lands, urban areas, construction and industrial sites, fuel stations, and garage operations; liquid wastes from toilets; open urination and defecation; and failed septic tanks. Point sources such as factories that discharge effluents directly into bodies of surface water are also concerns in Addis Ababa. Rivers in the city have also been used as a receptacle of other forms of solid and liquid wastes. As a result, the rivers are highly polluted with metals and some excessive nutrients that threaten human health and ecosystems. Waste enters water bodies from smaller cities too. In Bahir Dar, indiscriminate dumping of solid waste, connection of untreated sewage into the surface runoff drainage system, and other anthropogenic activities contribute to deteriorating water quality in the adjacent Lake Tana (Dagnew et al., 2014). The invasive water hyacinth has been present in Lake Tana since at least 2011.

Water pollution generates a variety of risks to human health, economic productivity, and ecosystem vitality. In Africa, it is estimated that water pollution, combined with inadequate sanitation, causes damages equivalent to 5% of GDP (Yohannes and Elias, 2017). In Ethiopia, polluted river water from urban areas is used by downstream residents to grow vegetables. Crops grown using the polluted water have the capacity to accumulate heavy metals above the recommended maximum limit. High concentration of trace metals such as Cadmium, Chromium, Copper, and Mercury in vegetables is evidence of industrial pollution. Heavy metals and excess nutrients have harmed aquatic life in Addis Ababa's rivers, and water pollution has also caused eutrophication and brought invasive aquatic plants to water bodies such as the Aba Samuel Reservoir (Yohannes and Elias, 2017).

Solid waste is another growing problem in Ethiopian cities, caused by rapid urbanization, population growth, and economic development. In urban centers in developing countries of Africa, between 30% and 60% of municipal solid waste (MSW) goes uncollected. Ethiopia has few sanitary landfills, most of which are not properly managed. Most solid waste (SW) is disposed of at open dumpsites, illegally littered, or openly burned. Little SW is recycled. As the proportion of plastics, packaging, and electronics in waste grows, the increased material diversity of waste intensifies the challenge.

Inadequate solid waste management (SWM) causes a range of environmental, social, public health and safety problems. The open burning of uncollected trash contributes to air pollution. It is estimated that the solid waste sector produced 2.1 Mt CO_{2e} in 2020. The landslide at an aging dumpsite in Addis Ababa in 2017, which caused the deaths of over 100 people, highlights the growing severity of the challenges posed by inadequate SWM. Leaching from improperly managed landfills can also pollute soil, groundwater, and surface water bodies, and solid waste litter can clog drainage systems contributing to flooding and water pollution.

Pollution problems do not exist in isolation. They are intricately interconnected and mutually reinforcing. In reality, connections between air pollution, water pollution, and solid waste are often largely unaddressed. For example, open burning of trash is not always considered in programs that address air quality, nor solid waste litter in efforts to improve water quality. Therefore, pollution management requires an integrated approach to establish multi-stakeholder and multi-sector institutional frameworks and effectively implement interventions that better align development and environmental management.

2.4 Institutional arrangements for pollution management in Ethiopia

To implement its green growth strategy, Ethiopia has developed an institutional framework for pollution management. The country has established relevant government agencies at different levels and adopted a set of policies and regulations for managing specific pollution issues. This section briefly reviews key stakeholders, organizational structures, and policy frameworks for pollution management.

Stakeholder mapping and key government agencies for pollution management

Pollution and pollution management involves many stakeholders, from the government to the private sector, civil society organizations, academic and research institutions, development partners and the public at large. Table 2 below lists key stakeholders, including government agencies and non-state actors.

Regarding air pollution, many government agencies at the federal, regional, and local levels are responsible for the management and regulatory functions for air quality, for example, the Federal Environmental Protection Authority (EPA) and the EPA of each municipality. Academic and research institutions generate and share knowledge, development partners finance air quality management (AQM) interventions through projects, and NGOs work to increase public awareness.

Water pollution is managed by the Ministry of Water and Energy (MoWE), relevant Environmental Protection Authority (EPA), and three river basin authorities (Abbay, Awash, Rift Valley Lakes). Their counterparts in regional and city governments are responsible for the management and regulatory functions for water pollution, respectively.

Stakeholders involved in SW generation and management include households, industry, construction companies, commercial entities, and public entities. Several government agencies are crucial to solid waste management, as is the private sector. The SW regulatory function is the responsibility of federal, regional, and city environmental protection agencies. The Ministry of Urban Development and Infrastructure and municipal government agencies are responsible for SWM operation. Academic and research institutions, development partners, and NGOs are also involved in SWM activities from public education to financing, research, and monitoring.

For each type of pollutant, the federal EPA needs to strengthen collaboration with the Ethiopian Standards Institute in setting up standards, monitoring implementation, and reporting for improved compliance.

Table 2. Key stakeholders for pollution management

Type of Stakeholder	Overall Pollution Management	Water and Sanitation	SWM	AQM
Leading government agencies	• Federal Environmental Protection Authority (EPA) • Ministry of Water and Energy • Ministry of Urban Development and Infrastructure • Ministry of Transport and Logistics • Ministry of Health	• Ministry of Water and Energy • Institute of Water Technology • Ministry of Health • Federal Environmental Protection Authority (EPA)	• Ministry of Urban Development and Infrastructure • Federal Environmental Protection Authority (EPA)	• Ministry of Transport and Logistics • Federal Environmental Protection Authority (EPA) • Ethiopian Standards Institute • Ethiopian Mereology Institute
Other government agencies (including local government units)	• Ministry of Finance • Ministry of Planning and Development • Regional and city Departments of Health & Sanitation	• Ministry of Education • Ministry of Planning and Development • Ministry of Finance • Regional and city Departments of	• Ministry of Planning and Development • Ministry of Finance • City Councils/Authorities • Addis Ababa SWM Agency	• Ministry of Industry • Ministry of Mines • Addis Ababa EPA • • Ministry of Finance

	• City water & sewerage agencies • Addis Ababa EPA	Health & Sanitation • City water & sewerage agencies • River basin authorities		
Non-state actors	• Civil Society Organizations • Private sector • NGOs • Community-based organizations (CBOs) • Professional associations • Academic/research institutions	• Civil Society Organizations • Private sector • NGOs • CBOs • Professional associations • Academic/research institutions	• Civil Society Organizations Authority • Private sector • NGOs • CBOs • Professional associations • Academic/research institutions	• Civil Society Organizations Authority • Private sector • NGOs • CBOs • Professional associations • Academic/research institutions

Table 3 below further lists key federal and Addis Ababa agencies that have direct mandates for pollution management, as stipulated in Proclamation No.1236/2021, which defines the powers and duties of the executive branches of the Federal Democratic Republic of Ethiopia and other relevant city-level regulations.

Table 3. Federal and city level government agencies responsible for pollution management in Ethiopia

	Agency	Responsibilities
Federal government	Environmental Protection Authority (EPA)	-Formulating national strategies, regulations, policies, standards, and procedures for environmental and social management, including pollution management. -Coordinating with other government agencies to develop and adhere to the relevant national strategies, regulations, policies, standards, and procedures. -Monitoring, supervising, and enforcing environmental policies and regulations at the national level. -Complying with international commitments and implementing international and regional environmental agreements where Ethiopia is a signatory.
	Ministry of Urban Development and Infrastructure (MUDI)	-Enacting national strategies and policy directives such as the Ethiopian Cities Sustainable Prosperity Goals. -Setting criteria and targets for urban sanitation, beautification, and greenery development plans. -Coordinating and leading the implementation of urban development plans. -Providing capacity-building support to regions to improve service delivery and ensure good governance in urban areas.

	Ministry of Health	-Enacting the sanitation and hygiene promotion strategy and guidelines. -Ensuring proper medical waste disposal.
	Ministry of Water and Energy	-Identifying measures that should be taken against pollution and damage to basins. -Determining quality standards of water used for various purposes; undertaking supervision to avert pollution.
	Ministry of Transport and Logistics	-Ensuring the establishment and implementation of regulatory frameworks to guarantee the provision of reliable and safe transport and logistics infrastructure. -Identifying and implementing measures that mitigate the impact of transport and logistics infrastructure and services on the environment and climate.
	Ministry of Planning and Development	-Initiating policy, strategy, and legislation with respect to development, national statistics, population, climate change and environment. -Coordinating, supporting, and following up on climate change and environmental activities.
Addis Ababa City Administration	Environmental Protection and Green Development Commission of Addis Ababa (EPGDA)	-Preparing and implementing environmental management strategy, policy, and plans at the municipal level. -Enforcing and monitoring pollution control measures in the city.
	AA SWM Agency (AASWMA)	-Implementing SWM policies and strategies at the municipal level. -Managing daily operations and supervision of SWM activities across the full waste value chain (receptacle, collection, pre-treatment, and disposal), including the Reppie Landfill site. -Contracting and engaging the private sector in waste collection, transportation, and recycling activities. -Working with other government agencies at municipal and sub-city levels and providing support for public awareness, research, and capacity building for SWM.
	AA Water and Sewerage Agency (AAWSA)	-Drinking water provision. -Liquid waste disposal.
	Health Bureau	-Ensuring proper medical waste disposal.
	Transport Bureau	-Vehicle emission control.

Policy and regulatory frameworks for pollution management

Ethiopia has a comprehensive policy and legal framework for general environmental management, including pollution management. Ethiopia's legislative commitment to environmental, social, and sustainable development objectives is highlighted by the inclusion of provisions in its Constitution (1995), the Environmental Policy, the Conservation Strategy, and various proclamations, regulations, and guidelines. In applying this commitment, Ethiopia has developed and adopted an extensive framework of environmental laws and regulations covering environmental and social management, including pollution management. Furthermore, Ethiopia has ratified International Conventions including the Rotterdam Convention via proclamation No. 278/2002 and the Basel Convention via proclamation No. 357/2003, which have an essential role in the improvement of the country's solid waste management systems. Table 4 summarizes the key policies, strategies, proclamations, and regulations relevant to pollution management in Ethiopia.

Table 4. Summary of policies, proclamations, and regulations relevant to pollution management

Item	Goals and Highlights	General pollution management	AQM	Water Pollution Management	SWM
Constitution of the Federal Democratic Republic of Ethiopia (1995)	• Articles 44 and 92 affirm that all people have the right to a clean and healthy environment. • The Government shall establish institutions and legal frameworks for environmental protection.	√			
Environmental Policy of Ethiopia (1997)	• To improve and enhance the health and quality of life of all Ethiopians and promote sustainable social and economic development through sound management of the environment and use of resources to meet the needs of the present generation without compromising future generations' ability to meet their own needs. • On waste management, the policy includes the following specific articles: Article 3(7) Human Settlement, Urban Environment, and Environmental Health; Article 3(8) Hazardous Materials and Pollution from Industrial waste; Article 3(9) Atmospheric Pollution and Climate Change Waste.	√			
Proclamation No. 513/1999	• Ban on the production and import of plastic bags with thickness of less than 0.03mm.				√
Environmental Impact Assessment Proclamation (No. 299/2002)	• Harmonizing and integrating environmental, economic, cultural, and social considerations into decision making processes in a manner that promotes sustainable development.	√	√	√	√
National Solid Waste Management Proclamation (No. 513/2007)	• Promotes community participation to prevent adverse effects and enhance benefits resulting from solid waste management. • Provides for preparation of solid waste management action plans. • Has civil and penal liability provisions. • Enhances capacities at all levels to prevent possible adverse impacts while creating economically and socially beneficial assets out of solid waste.				√
Urban Development Policy (2006)	• Intersects with the National SWM Proclamation. • Promotes proper disposal of urban solid and liquid wastes.	√		√	√

Proclamation Provided for the Establishment of Environmental Protection Organs (No. 295/2002)	• Defines coordinated but differentiated responsibilities of environmental protection agencies at the federal and regional levels, and sector environmental units. • Establishes a system that promotes sustainable use of environmental resources, thereby avoiding possible conflicts of interest and the duplication of efforts.	√					
Environmental Pollution Control Proclamation (No. 300/2002)	• States that no one shall pollute the environment. • Promotes the proper management of hazardous and non- hazardous wastes. • Includes articles on ensuring the collection, transportation, recycling, treatment, or safe disposal of municipal waste through the institution of an integrated municipal waste management system.	√		√	√		√
Public Health Proclamation (No. 200/2000)	• Addresses waste generated by hospitals and health centers. • Aims to ensure compliance with environmental standards.			√	√		√
Proclamation on Ethiopian Water Resource Management (No. 197/2000)	• Establishes a framework for water use. • Includes water polluter service fees.				√		
Fisheries Development and Utilization Proclamation No. 315/2003	• The Proclamation gives support to the industry's involvement in discussions around setting targets for managing SW and plastic pollution and in the management of nets. It is of limited relevance otherwise as it does not provide support to preparing regulations that would reduce plastic waste loads.				√		√
River Basin Councils and Authorities Proclamation No. 534/2007	• The Proclamation has a direct connection to lakes, rivers, and riparian areas, and an indirect connection through IWRM to the lower sub-catchments in terms of managing plastic waste if these become a significant source of plastic pollution.				√		√
Regulation for the Prevention of Industrial Pollution (No. 159/2008)	• Requires annual compliance reporting from factories.			√	√		√
A Proclamation to Provide for Urban Plans No. 574/2008	• A wider perspective on the challenges relating to managing waste, at least of a spatial dimension. • The Proclamation was assessed as medium relevance in terms of providing direction in managing land development and SW management in urban areas,						√

	including in terms of providing SW management services.						
SW Management Manual (2012)	• This is a national document used to provide support for the management of SW in Ethiopia. It outlines types of waste and appropriate management, integrated approaches, landfill types, and provides support for investing in resource recovery.						√
Industrial Chemical Registration and Administration Proclamation (No. 1075/2018)	• National system for registration and administration of industrial chemicals. • Aims to prevent and control the adverse effects arising from the mismanagement of chemicals.			√	√		√
Hazardous Waste Management and Disposal Control Proclamation (No. 1090/2018)	• Creates a system for the environmentally sound management and disposal of hazardous waste. • Prevents damage to human and animal health, the environment, biodiversity, and property due to the mismanagement of hazardous waste.						√
Electric and Electronic Waste Management and Disposal Regulation (No. 425/2018)	• Addresses environmental impacts of e-waste. • Regulates its generation, recycling, and disposal. • Makes producers, importers, and sellers responsible for e-waste management.						√
Ethiopian Criminal code article No. 520 (a,b,c)	• Stipulates that whoever fails to manage hazardous wastes or materials in accordance with the relevant laws; or fails to label hazardous wastes or materials; or unlawfully transfers hazardous wastes or materials, is punishable.	√					
Integrated Urban Sanitation and Hygiene Strategy (IUSHS)- 2016	• To reduce, recycle or reuse 50% of all SW generated in medium and large towns and cities by 2025 (interim target of 20% by 2020). • To dispose of 100% of the remaining SW in controlled tipping and sanitary landfill sites that fully comply with 2014 Guidelines by 2030 (interim target of 50% by 2020). • To ensure safe disposal of 100% of health care waste from all health care facilities by 2025 (interim target of 95% by 2020). • To enforce safe treatment, reuse, or disposal of industrial liquid and solid wastes to ensure ecosystem, agricultural, and human protection from all industries by 2035 (interim target of 30% of all industries by 2020.				√		√

Although the necessary environmental and social management institutions and legal frameworks are largely in place, the inadequate human resources and frequent turnover of technical staff, lack of coordination and integration between sectors and oversight bodies, weak enforcement, insufficient evaluation of policies and regulations, and inadequate budgets exacerbate the challenge of effective implementation and enforcement of these laws.

Weak technical capacity in the regulatory and management functions of pollution management at all levels has contributed to ineffective direction and implementation of pollution management interventions. Furthermore, frequent restructuring of ministries with changing responsibilities has been a challenge. For example, the federal environmental agency, which is responsible for pollution control, was restructured three times in the last six years. The reorganization of the EPA to entirely focus on the regulatory function seems good, but it has to be supported with commensurate capacity in staffing and resources to be effective in its pollution control activities. A recent World Bank program has supported the strengthening of Ethiopia's federal Environmental and Social Impact Assessment (ESIA) system.

The allocation and use of resources for competing uses requires more dialogue and greater coordination among stakeholders. The existing regulatory framework is built without clear arrangements for effective coordination among the various agencies and institutions involved in pollution management. Generally, there are inadequate coordination and collaboration mechanisms for pollution management at all levels. Thus, it is critical to establish and strengthen coordination and collaboration mechanisms both at federal and regional/city government levels in consultation with relevant stakeholders.

Both federal and regional/city level institutions lack comprehensive monitoring, evaluation, and knowledge management systems related to pollution management. Lack of information is a constraint for pollution management because data in most cases are not current and reliable.

Chapter 3 Air Pollution

Globally, air pollution has been a pressing environmental problem that undermines health and economic productivity. The main air pollutants include particulate matter (PM), carbon monoxide (CO), nitrogen oxides (NOx), sulfur oxides (SO2), volatile organic compounds (VOC), and ozone.

Air pollution is the largest environmental risk factor for poor health.[3] Fine particulate matter – with an aerodynamic diameter of less than 2.5 micrometers, or $PM_{2.5}$ – is considered the most relevant indicator for urban ambient air quality as well as indoor air quality and an important risk factor for premature death around the world (Health Effects Institute, 2020). It can pass the barriers of the lung, enter the blood stream, and destroy the integrity of the blood-brain barrier, thus causing premature deaths as well as respiratory, cardiovascular, and neurological diseases (Peeples, 2020; Bowe et al., 2019; Shou et al., 2019). Moreover, air pollution has recently been associated with an increased incidence of infections, such as influenza and COVID-19 (Zivin et al., 2021; Petroni et al., 2020).

In Ethiopia, particulate matter pollution is ***the second leading risk factor for pre-mature death***, after child and maternal malnutrition (IHME, 2020). Household air pollution is the most prominent contributor to mortality, causing 67,800 premature deaths in 2019. While ambient air pollution is responsible for a lower health burden,[4] it is a growing health problem in urban areas (Berhane et al., 2016). Aware of its ambient pollution situation, Addis Ababa recently prepared an air quality management (AQM) plan, based on the recommendations provided by an earlier study (Xie et al., 2021). However, the rest of Ethiopia has insufficient air quality (AQ) monitoring, a weak understanding of the air pollution situation, and a lack of comprehensive air pollution control plans. This chapter addresses this gap by providing a brief overview of the household air pollution situation and an analysis of ambient air pollution in three cities (Addis Ababa, Bahir Dar, and Hawassa). Chapter 7 follows this analysis with key recommendations to improve air quality in urban Ethiopia.

3.1 Household air pollution

Household Air Pollution (HAP) concerns the air inside buildings, such as homes and workplaces (EPA, 2014), and is determined by pollutant emissions (e.g., cooking, heating) and a building's structure, materials, and ventilation. Indoor air pollution poses the world's largest single environmental health risk (Ritchie & Roser, 2019; WHO, 2014). It is responsible for the spread of numerous diseases and has become a greater concern during the COVID-19 pandemic. HAP is a critical concern particularly in Sub-Saharan Africa (SSA), as the region has the world's highest case numbers of premature mortality and morbidity related to HAP (GeoHealth Hub, 2014). Many SSA countries, including Ethiopia, have gradually recognized the risk air pollution poses to public health (EFCCC, 2018; GeoHealth Hub, 2014).

Key drivers of household air pollution

HAP is mostly attributable to indoor activities that rely on solid biomass combustion, such as cooking, heating, smoking tobacco, and burning waste (Embiale et al., 2020; Ritchie & Roser, 2019; EFCCC, 2018; EPA, 2014). Solid biomass that is wet or of low quality takes longer to burn and emits harmful pollutants

[3] In 2019, it was responsible for more than 213 million disability-adjusted life years lost, which is substantially higher than any other environmental risk factor (http://ghdx.healthdata.org/gbd-results-tool, accessed January 2022)
[4] In 2019, there were 8,960 deaths due to ambient air pollution in Ethiopia (http://ghdx.healthdata.org/gbd-results-tool, accessed March 2021).

such as black carbon, PM, carbon dioxide (CO_2), and nitrogen oxide (NO) (CCA, 2021c; Kumie et al., 2009). Moreover, buildings with poor ventilation, such as huts without windows, may have poor air quality as air pollutants are trapped inside instead of being dispersed (EPA, 2014; GeoHealth Hub, 2014; Kumie et al., 2009). Ambient air pollution from nearby traffic and other activities also leaks into buildings, making such pollution difficult to address (EFCCC, 2018; NASEM, 2016; GeoHealth Hub, 2014).

Lu (2018) estimated that about 54% of people living in low- and middle-income countries (LMICs) use solid biomass fuels such as wood, coal, and dung to heat their homes and cook on traditional stoves. Balidemaj et al. (2021) arrived at a similar conclusion, showing that about 3 billion people burn solid biomass fuels on traditional stoves for cooking and/or heating. Inefficient cooking appliances are a primary source of indoor air pollution in LMICs (AAEPGDC, 2020; NASEM, 2016; Embiale et al., 2016).

Across Ethiopia, 93% of all energy consumed is in residential households (Benka-Coker et al., 2018) and about 95% of households use biomass fuels as their primary energy source; biomass fuel combustion represents the most significant source of HAP in the country (Adane et al., 2021; EFCCC, 2018). Furthermore, about 31% of the Ethiopian population lives below the international poverty line of $1.90 per day per capita. These low-income households rely on fuel wood – as the most affordable energy source – which represents 76% of Ethiopia's total fuel consumption per year (ESMAP, 2021; CCA, 2021; World Bank, 2020).

Impacts of household air pollution

Chronic exposure to HAP can cause severe health issues – lung and heart diseases, diabetes, etc. (Taghizadeh-Hesary et al., 2020; EPA, 2014b). Smoke emitted from indoor biofuel burning contains PM (such as $PM_{2.5}$), which can inflame airways, reduce the effectiveness of the human body's immune system, and decrease the oxygen available in the blood (WHO, 2021; Taghizadeh-Hesary et al., 2020). Worldwide, approximately 2.3 million people die annually from diseases connected to household air pollution, including pneumonia, stroke, ischemic heart disease, chronic obstructive pulmonary disease (COPD), and lung cancer (IHME, 2022). Women and children are impacted the most, due to their prolonged use of indoor spaces for domestic activities such as cooking (GeoHealth Hub, 2014). Studies in Ethiopia show that the exposure from inefficient cooking systems during a cooking session up to 4 hours daily is equivalent to smoking 40 packs of cigarettes per day (Embiale et al., 2019; Tefera et al., 2016).

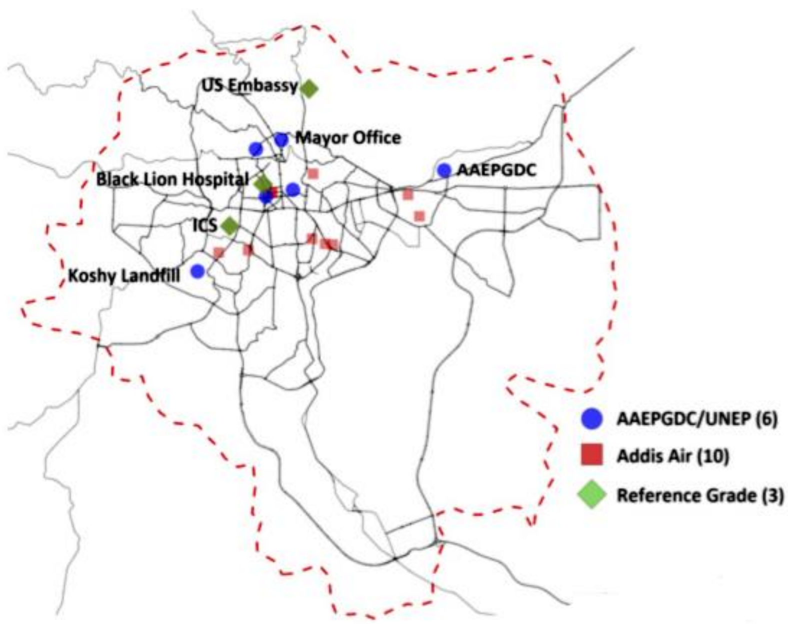
Exposure to HAP also increases the spread of bacterial and viral infections. For example, Akand et al. (2018) found that bacterial meningitis – a disease that is a large-scale issue in SSA – is facilitated by indoor air pollution. This is particularly concerning in the context of the COVID-19 pandemic, as indoor air pollution reduces immune responses and increases the risk of more severe infections (CCA, 2021d). Studies have also shown that HAP can affect mental health, causing depression and anxiety by affecting mental function and increasing heart rates (Taghizadeh-Hesary et al., 2020).

As previously noted, HAP is responsible for a large number of premature deaths in Ethiopia. Moreover, it is associated with many of the country's top causes of air-borne diseases: Asthma for example, which is Ethiopia's eighth most common disability (AAEPGDC, 2020), and acute upper respiratory infections which account for about 7% of the country's hospital admissions (EFCCC, 2018). HAP also negatively impacts the natural environment. The pollutants from cooking and energy use include many greenhouse gas emissions, such as CO_2, methane, and black carbon, that contribute to climate change (WHO, 2021). For example, CCA (2021c) estimated that wood fuel emits about one gigaton of CO_2 annually, some 2% of total global emissions. Additionally, inefficient biomass fuels contribute to environmental degradation because of how the fuels are sourced (Hosier et al., 2017). For example, wood is the most consumed fuel, including 91.2 million tons of firewood and 4.2 million tons of charcoal (Benka-Coker et al., 2018). This usage contributes to deforestation and reduces biodiversity (Das et al., 2021; Hosier et al., 2017). Furthermore, these activities can develop social conflicts related to natural resources, such as those between refugees forced to find wood for energy, and local communities (Benka-Coker et al., 2018). ESMAP (2021) recently estimated that traditional cooking practices cost Ethiopia alone about US$35.44 billion annually in health, social, and environmental-related impacts.

3.2 Ambient air pollution

Building on the most recent studies (Guttikunda, 2022; Xie et al., 2021), this section provides an overview of air pollution problems, estimates the impact of ambient $PM_{2.5}$ on health, and analyzes the main pollution sources in the three selected cities.

Figure 6. Location of air quality monitors in Addis Ababa



*Note: the reference monitors installed by the US Government and the GEO Health Hub are shown in **green**; the monitors by AAEPGDC in **blue**, and by Addis Air in **red**.*

Ambient air quality in Addis Ababa, Bahir Dar, and Hawassa

Rapid urbanization and industrialization have exposed most of the population in the cities studied to increasing levels of pollution. In Addis Ababa, an analysis of visibility data suggests that today air quality is approximately 1.6 times worse than it was in the 1970s (ASAP East Africa, 2019). Three reference grade monitoring stations have been operational in Addis Ababa for several years. Two were installed and maintained by the US Government and one by the Eastern Africa GEO Health Hub team. They use an approved beta attenuation method. In addition, six kunak-cloud sensors were recently installed by AAEPGDC/UNEP, and 10 sensors that use a light-scattering method to measure $PM_{2.5}$ concentration were installed by Addis Air. These sensors are low-cost and experimental and require quality-controlled calibration before their outputs can be used for policy dialogue. While these sensors encountered some operational challenges, which lead to discontinuity in available data, their extensive monitoring network in Addis Ababa provides a representative spatial footprint of $PM_{2.5}$ pollution (Figure 6). Table 5 provides the available $PM_{2.5}$ concentrations measured in different locations of the capital for the latest year for which data are available.

Table 5. $PM_{2.5}$ concentration measurements in Addis Ababa in 2020*

Type of monitor	Location	Area Type	$PM_{2.5}$ concentration ($\mu g/m^3$)*
Reference grade monitors	International Community School (ICS)	Largely residential	31
	US Embassy	Office buildings/green area	24
	Black Lion Hospital	Traffic/residential	43
Low-cost sensors	Arat-Kilo	Residential	22
	Churchill Avenue	Traffic/commercial/school	46
	EU delegation to AU	Residential/AU headquarters/traffic	56
	EU delegation to Ethiopia	Green area/traffic	24
	ICS/Bisrate Gebriel	Residential	24
	ILRI/CCAFS	Green area/offices	24
	Kirkos	Commercial/residential	29
	Lambert	Residential	26
	Lycee Francais	Traffic/commercial/school	45
	Peacock Park-Bole Atlas	Green area/river/urban agriculture	24

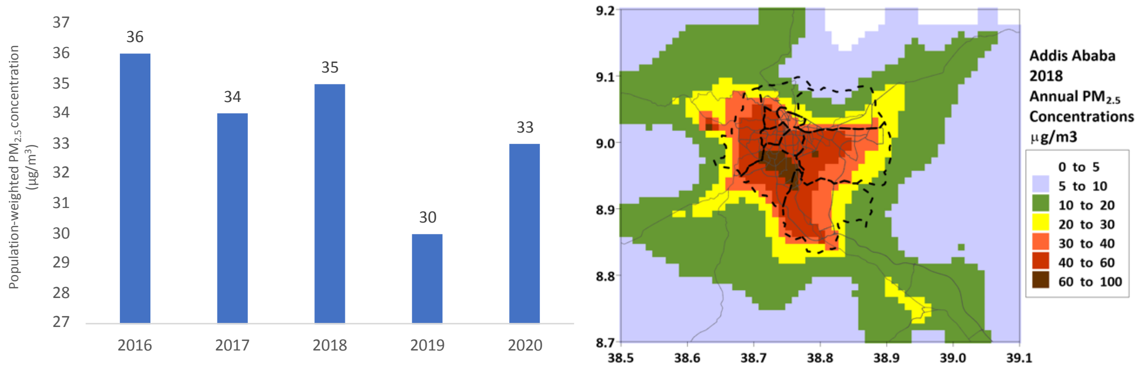
** For some monitoring stations, the $PM_{2.5}$ concentration represents averages for the past two years (Churchill Avenue, ILRI/CCAFS, Lycee Francais, and Peacock Park-Bole Atlas) or three years (Black Lion Hospital).*

Source: Xie et al., 2021.

Using the existing data and the population exposed in each monitoring location, the annual $PM_{2.5}$ population-weighted average was estimated between 30 $\mu g/m^3$ and 36 $\mu g/m^3$ for 2016-2020 (Figure 7). Accordingly, the average concentration in Addis Ababa was estimated at ***34 $\mu g/m^3$*** for a typical non-COVID year. This is more than six times higher than the current WHO guideline.[5]

[5] The updated WHO Air Quality Guideline for annual average $PM_{2.5}$ is set at 5 $\mu g/m^3$, based on evidence of health effects of long-term exposure to $PM_{2.5}$ (WHO, 2021).

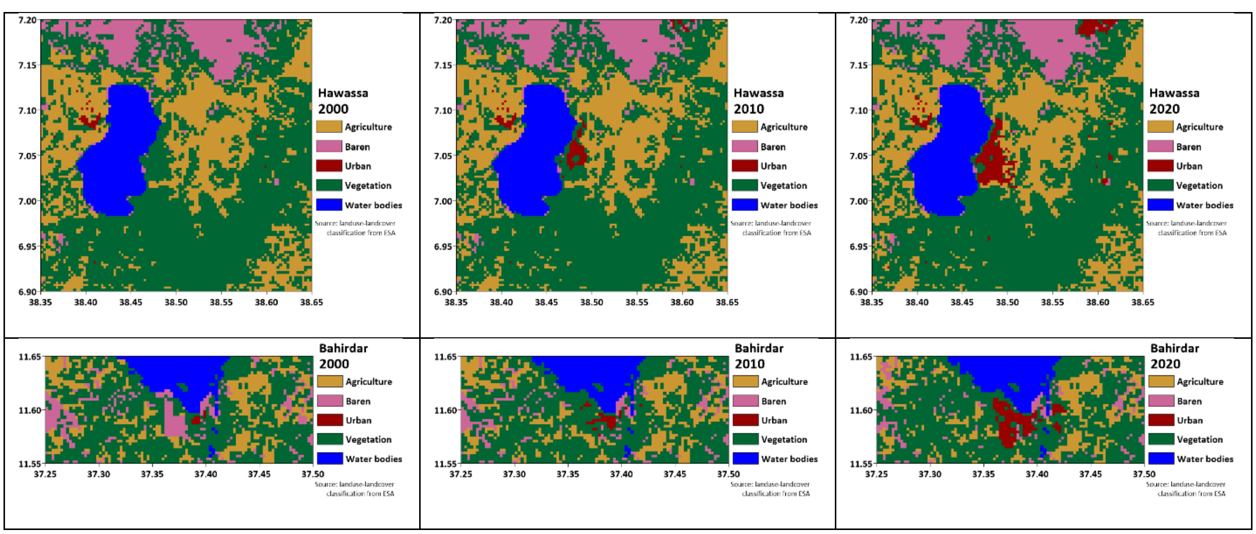
Figure 7. Annual $PM_{2.5}$ concentration in Addis Ababa



Source: Xie et al., 2021

Hawassa and Bahir Dar each have populations of nearly 400,000 people, and each contribute about 0.5 percent of the country's GDP. They also present interesting differences: while the economic activities in Hawassa are dominated by agro-processing and garment and textile industries, Bahir Dar stands out as a regional metropolitan hub and resort city, with continued construction of hotels and housing to accommodate growing tourist and resident populations. Figure 8 presents a summary of land cover and land use for Hawassa and Bahir Dar for the years 2000, 2010, and 2020. This is a proxy for urbanization which can be linked to growing demand for residential and commercial amenities, transportation, waste management, and construction material – all with direct linkages to energy use and subsequent pollution in the cities.

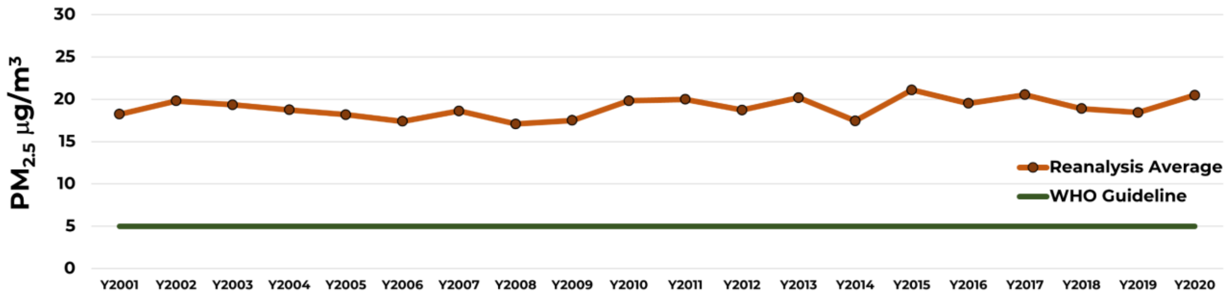
Figure 8. Land cover and land use in Hawassa and Bahir Dar



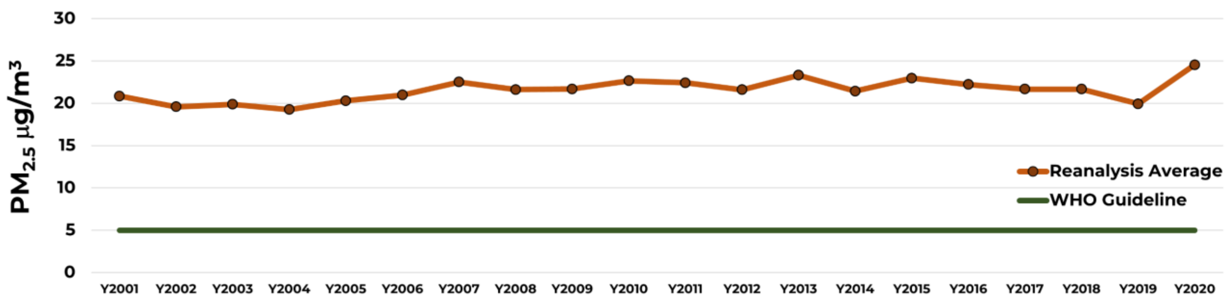
Like Addis Ababa, economic growth in the two cities was accompanied by a rise in pollution levels. Although no operational ground monitors exist, an analysis of long-term satellite observations, coupled with results from chemical transport models utilizing detailed emission inventories, shows that in both cities current $PM_{2.5}$ concentrations are well above the WHO guideline value of 5 µg/m^3 (Figure 9). Using the most recent non-COVID period data (2016-2019), the annual $PM_{2.5}$ concentration is estimated at 20 µg/m^3 in Bahir Dar, and 22 µg/m^3 in Hawassa. In the absence of any locally available information, the results from these global modeling systems are used to conduct an initial assessment of emission levels, pollution trends, and health impacts. These are just indicative estimates for the two cities due to the absence of ground monitored data and population distribution at representative locations.

Figure 9. Long-term trends of annual $PM_{2.5}$ concentration

(a) Bahir Dar



(b) Hawassa



Main sources of air pollution

Identifying the main sources of air pollution and quantifying their actual contribution to the $PM_{2.5}$ concentration are essential steps to designing effective strategies for cleaner air. A detailed emissions inventory was developed for the Greater Addis Ababa region, at a spatial resolution of 1 km^2, based on data collected from Ethiopia's environmental and statistical offices and also publicly available information relevant for energy and emissions analysis, such as road networks, vehicle sales and registration numbers, vehicle usage, maps of points of interest, energy demand and consumption rates, energy demand for residential cooking and heating, and waste management. The results, illustrated in blue in Table 6, show that transport is the main source of $PM_{2.5}$, NO_x, SO_2, and CO_2 emissions, residential activities, such as cooking and lighting, are the top sources of CO and VOC, and resuspended dust from roads accounts for the biggest emitter of PM_{10}.

Table 6. Total emissions estimated for Addis Ababa's airshed (tons, 2018)

	$PM_{2.5}$	**PM_{10}**	**NO_x**	**CO**	**VOC**	**SO_2**	**CO_2**
Transport	7,850	8,050	120,100	94,200	10,750	4,550	8,683,250
Residential	7,300	7,450	100	101,500	15,100	900	157,800
Industry	6,650	7,700	2,950	47,000	13,700	850	92,250

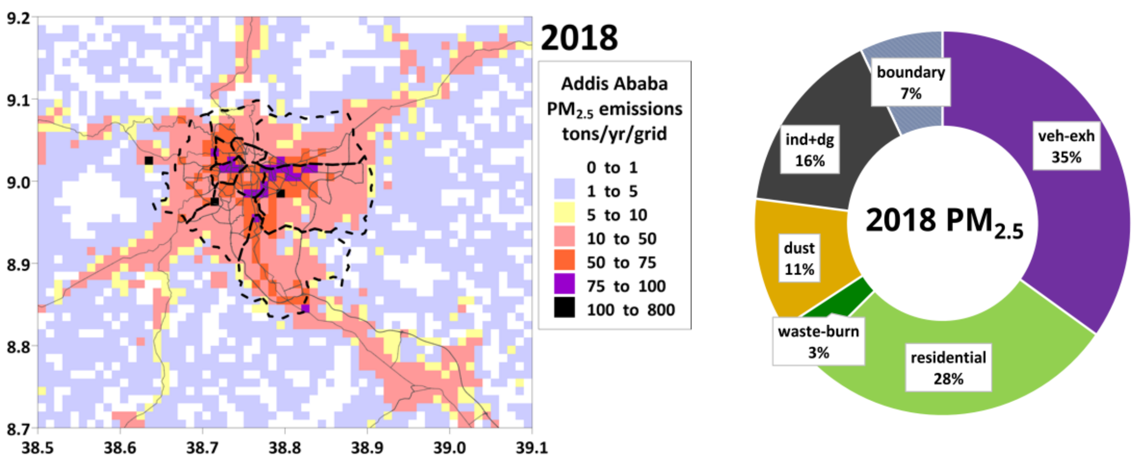
Dust	3,950	26,100	-	-	-	-	-
Open waste burning	850	900	-	4,050	800	-	5,400
Diesel generators	200	200	1,250	3,950	1,750	50	120,000
Total	**26,800**	**50,400**	**124,400**	**250,700**	**42,100**	**6,350**	**9,058,700**

Note: The numbers in blue reflect the greatest emissions for each category.

Source: Xie et al., 2021.

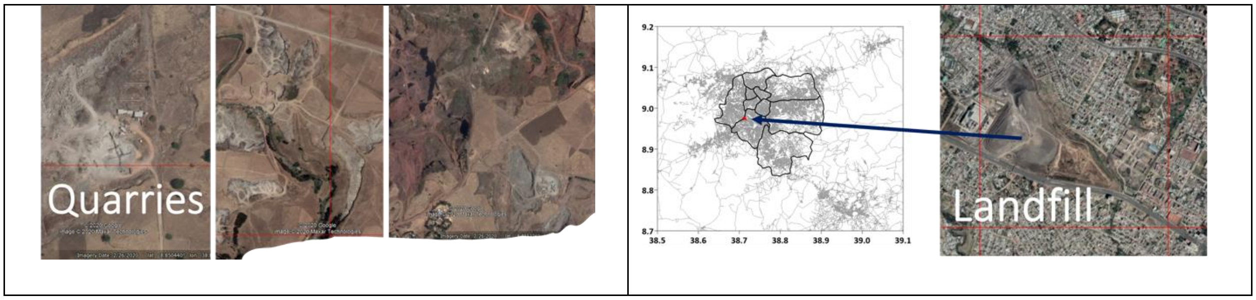
An open-source Comprehensive AQ Model with extensions (CAMx) and meteorological data processed through the Weather Research Forecasting model were used to transform the above emissions into pollutant concentrations for a source apportionment analysis. The spatial spread of emissions (highlighting the hotspots within the city limits), estimated annual average $PM_{2.5}$ concentrations for the airshed, and estimated contributions of sources within the airshed and those outside (boundary conditions) are presented in Figure 10. This analysis concluded that, in 2018, the main contributors to $PM_{2.5}$ pollution in Addis Ababa were vehicle exhaust (35 percent), residential activities (28 percent), industries (16 percent) and resuspended dust (11 percent). Examples of some point sources of interest, mapped from scanning the Greater Addis Ababa region, are presented in Figure 11. A closer look at the spatial distribution of industrial sources found that heavy industrial polluters are scattered along the edge of the city, requiring a shared effort to manage $PM_{2.5}$ by the city and surrounding regions.

Figure 10. Source contributions to $PM_{2.5}$ concentration in Addis Ababa, 2018



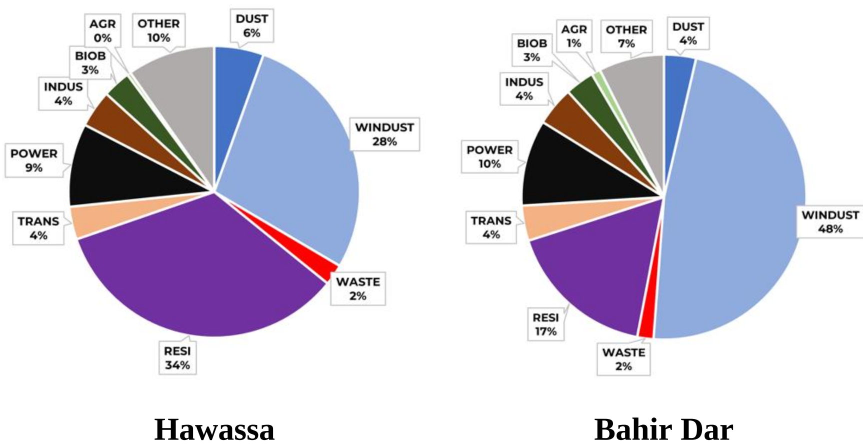
Sources: Xie et al., 2021

Figure 11. Examples of point sources of air pollution in Addis Ababa



Despite no data on air pollution sources by sector available for the cities of Bahir Dar and Hawassa, a source contribution assessment is available from the same global modeling system used to estimate air quality. These sources are presented in Figure 12. While the overall pollution levels are similar in the two cities, there are substantial differences in the amount of pollution coming from various sources. Residential activities were the main $PM_{2.5}$ contributor in Hawassa. Wind dust stood out as the main pollution source in Bahir Dar, contributing nearly half of the city's pollution.

Figure 12. Source contributions to $PM_{2.5}$ concentration in Bahir Dar and Hawassa, 2018



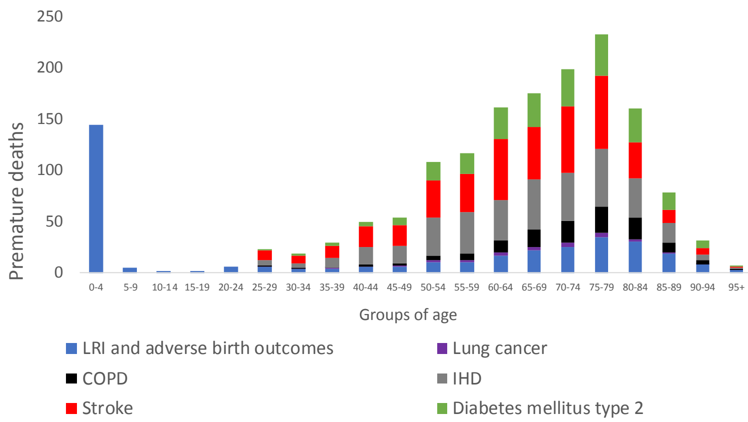
Among combustion sources, residential cooking and lighting is the biggest contributor, followed by industry, including power generation. Dust--from roads and wind-blown-- is a significant contributor to the air pollution problem as well. The presence of barren lands around the city of Bahir Dar exacerbates the dust levels, compared to the city of Hawassa which is surrounded by more vegetation. As next steps, in order to differentiate between the dust contributions of local and long-range transport (like dust storms), airshed-level high resolution (~1-km) emissions and pollution modeling is required, similar to the assessment conducted for Addis Ababa.

Health impacts

Several epidemiological studies have revealed strong correlations between long-term exposure to $PM_{2.5}$ and premature mortality and morbidity (Wu et al., 2020; Cohen et al., 2017; Apte et al., 2015). This section quantifies these impacts in physical terms for Addis Ababa, then presents the results of a rapid valuation conducted for the other two cities. Chapter 6 provides an economic valuation of these impacts.

The impacts of the long-term exposure to ambient $PM_{2.5}$ include ischemic heart disease, lung cancer, chronic obstructive pulmonary disease, lower respiratory infections, stroke, type 2 diabetes, and adverse birth outcomes (GBD 2019 Risk Factors Collaborators, 2020). We estimated the number of premature deaths attributable to the ambient $PM_{2.5}$ concentration for Addis Ababa, using data on: (i) mortality by disease and age group at the national level, based on IHME (2020); (ii) an adjustment for Addis Ababa, considering the differences in population distribution by age group between the city and the national level, and (iii) the proportion of deaths attributable to $PM_{2.5}$, calculated based on relative risk factors derived from the Global Burden of Disease methodology (IHME, 2020). Accordingly, exposure to ambient $PM_{2.5}$ is estimated to cause about 1,600 premature deaths annually. Stroke, ischemic heart disease, and lower respiratory infections are the leading causes of $PM_{2.5}$-related mortality. Elderly people between 60 and 84 years of age are the most affected, accounting for about 58 percent of premature deaths (Figure 13). In addition to mortality, exposure to ambient $PM_{2.5}$ is responsible for about 4,100 Years Lived with Disability (YLDs) annually.

Figure 13. Premature deaths due to $PM_{2.5}$ exposure in Addis Ababa, by age group

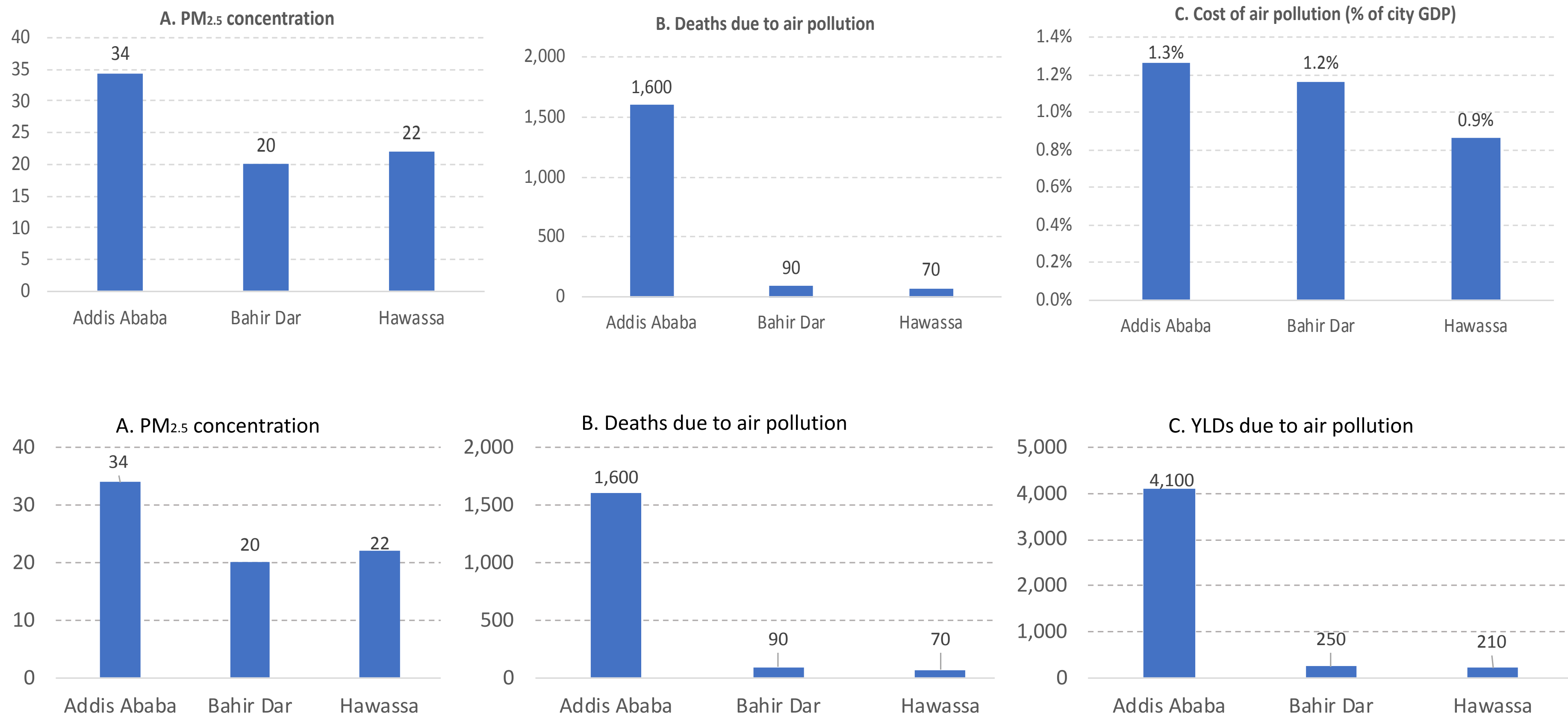


Notes: IHD = ischemic heart disease; LRI = lower respiratory infections; COPD = chronic obstructive pulmonary diseases.

Source: Xie et al., 2021, based on data from IHME (2020) and GBD 2019 Risk factors collaborators (2020).

The same methodology was used to quantify the impacts of ambient $PM_{2.5}$ on health in Bahir Dar and Hawassa. Figure 14 presents the health effects for the three cities. These results are conservative, as they only account for specific outcomes caused by exposure to $PM_{2.5}$. Other pollutants may cause additional negative effects. For example, Flanagan et al. (2022) found that in Adama, there is a tendency towards an association between ambient NO_x and NO_2 maternal exposure during pregnancy and an increased risk of fetal death.

Figure 14. Impact of ambient air pollution in selected Ethiopian cities



Sources: Xie et al., 2021 for Addis Ababa and authors' calculations for Bahir Dar and Hawassa.

Chapter 4 Water Pollution

4.1 Introduction

Water pollution is a complex issue due to the interplay of atmospheric conditions, geography, and multiple point and non-point pollution sources. It also involves many different stakeholders from various sectors. In addition to the complex set of factors that affect water quality (WQ) – such as industrial effluent, agricultural and urban run-off, and improper disposal of untreated sewage and solid waste – these factors also affect different water sources, such as surface water or groundwater, in different ways.

Groundwater provides more than 90% of the domestic and industrial water supply in Ethiopia, while most water used for irrigation comes from surface water (Kebede, et al., 2018). Ethiopia benefits from multiple major rivers which provide a sizable amount of surface water. However, these water flows are unequally distributed and concentrated in areas above 1500m in elevation. This fact – together with the country's varying hydrogeology throughout, which leads to a high variability in aquifer productivity – causes Ethiopia to have areas with plentiful water and others where water is scarce. In addition to water scarcity, many regions in Ethiopia also struggle with low water quality, especially when it comes to surface waters. Major lakes, such as Lake Tana, are suffering from high nutrient loads and other pollution that can have major impacts on the environment, economy, and human health. Over the last two decades, this problem has gotten increasingly worse from a variety of factors, such as industry near bodies of water, rapid population growth, and insufficient government oversight.

This chapter explores the factors that affect water quality, the current water quality situation, and the effects of water quality on the environment, economy, and human health in Addis Ababa, Bahir Dar, and Hawassa. The discussion in this chapter is based on a comprehensive review of the literature and available documents as well as discussions with government counterparts; no on-the-ground measurements were conducted. Lastly, even though the chapter focuses on only three cities, it is likely that the overall findings extend, to varying degrees, to the many urban areas in Ethiopia.

4.2 Overview of Ethiopia's water quality problems

Water quality standards

In Ethiopia, water quality is measured using a variety of parameters with standards set by a number of different agencies. The most common parameters, which are also used in this study, are defined in Table 7. Furthermore, the most relevant standards for this study are set by the Ethiopian EPA (EEPA). The threshold values set by the EEPA, and values that are widely accepted internationally, are also included in Table 7.

Table 7. Overview of common WQ parameters

Parameter	Unit	Ethiopian/ International Standard	Definition
Electrical Conductivity (EC)	µS/cm	1000/1500[a]	The ability of the tested water to conduct electricity, an indication of the amount of salt and inorganic chemicals it contains.
Total Dissolved Solids (TDS)	mg/L	400/500[a]	The amount of solids dissolved in water.
Total Suspended Solids (TSS)	mg/L	50/--	The amount of (non-dissolved) suspended particles present in water.
Orthophosphate as Phosphorus (PO_4-P)	mg/L	0.025/0.20[c]	The amount of phosphorus present in the form of the PO_4 ion. For example, 1 mg/L of PO_4-P means that there is 1 mg/L of phosphorus that is bound as PO_4 (i.e. not 1 mg/L of PO_4)
Total Phosphorus (TP)	mg/L	0.025/--	The total amount of phosphorus present in all forms.
Nitrate Nitrogen (NO_3-N)	mg/L	11.3/11.3[e]	The amount of nitrogen present in the form of the NO_3 ion. For example, 1 mg/L of NO_3-N means that there is 1 mg/L of nitrogen that is bound as NO_3 (i.e. not 1 mg/L of NO_3)
Nitrate (NO_3)	mg/L	50/50[e]	The amount of the nitrate ion present.
Nitrite Nitrogen (NO_2-N)	mg/L	0.1/0.1[b]	The amount of nitrogen present in the form of the NO_2 ion. For example, 1 mg/L of NO_2-N means that there is 1 mg/L of nitrogen that is bound as NO_2 (i.e. not 1 mg/L of NO_2)
Nitrite (NO_2)	mg/L	0.1/0.1[b]	The amount of the nitrite ion present.
Ammonium Nitrogen (NH_4-N)	mg/L	0.2/--	The amount of nitrogen present in the form of the NH_4 ion. For example, 1 mg/L of NH_4-N means that there is 1 mg/L of nitrogen that is bound as NH_4 (i.e. not 1 mg/L of NH_4)
Chemical Oxygen Demand (COD)	mg/L	--/25[c]	The amount of oxygen required to chemically oxidize any inorganic nutrients or organic materials in water.
Biological Oxygen Demand (BOD)	mg/L	5/5[a]	The amount of oxygen required for microorganisms to aerobically decompose organic matter (depends on temperature and time). BOD_5 is commonly used and denotes the 5-day BOD at 20°C.
Dissolved Oxygen (DO)	mg/L	4/4.5[a]	The amount of oxygen dissolved in water.

Turbidity	NTU	--/1[d]	The optical clarity of water. Lower numbers indicate higher clarity.
pH	--	6-9/6.5-9[a]	The acidity/basicity of water. A value of 7 indicates neutral with lower numbers indicating acidic conditions and higher numbers basic conditions.
Heavy Metal Concentration	μg/L	Varies/ Varies[d]	Concentration of a given heavy metal.

Note: Ethiopian standards are from the EEPA (EEPA and UNIDO 2003), whereas the international standards come from a variety of agencies ([a]US EPA, [b]Aus/NZ, [c]EU, [d]WHO, [e]FAO).

Major sources of water pollution

Before describing the water quality situation, it is important to first discuss the major factors that affect water quality in order to understand how the described concerns can be addressed. First, water quality in all three study cities is impacted by industrial effluents. There is an abundance of industrial sites, most of which discharge their untreated wastewater into nearby streams and rivers. In Addis Ababa, for example, about 89% of the volume of wastewater is estimated to come from just three industries, namely the leather and footwear, food and beverages, and textiles industries (Getachew, et al., 2021). These wastes then lead to contamination of waterways with various organic and inorganic chemicals, such as detergents, heavy metals, salts, and dyes (Yohannes and Elias, 2017), that then make the water inhospitable to aquatic life and unacceptable for human consumption. This source of contamination is significant, as found by a spatio-temporal analysis of pollution in the Little Akaki river (Angello, Tränckner & Behailu, 2020) and by studying the Lake Hawassa (Lencha, Tränckner & Dananto, 2021; Mereta, et al., 2020) and Lake Tana watersheds (D. Berihun, 2017; Mehari, Gebremedhin & Ayele, 2015; Wondie, 2009).

Pollution due to agricultural and urban run-off is a second major factor impacting water quality in these cities. This pollution generally comes from water that flows into the streams and rivers from agricultural lands, construction areas, industrial sites, business operations (such as fuel stations and garage operations), and residential areas (human and other liquid wastes) due to irrigation, rain, or stormwater. Sediment inflows and soil erosion due to deforestation can also contribute to this pollution. Overall, this type of pollution is much harder to control since it usually comes from non-point sources. Nonetheless, it is a significant contributor to water quality concerns in these cities (Angello, Tränckner & Behailu, 2020; Haile & Mohammed, 2019; Wondie, 2009).

Pollution from non-point sources is also much more difficult to quantify. While rain and stormwater, for example, will wash pollution from these sources into waterways, water quality tends to be better during the wet season than the dry seasons, due to dilution of both the non-point and point sources present in a city. For example, a detailed study in the Little Akaki River catchment illustrated that, if only point sources existed, the extent of the water quality improvement during the rainy season should be larger than what is observed, implying that there are non-point sources from agricultural and urban run-off that get activated during the rain (Adugna, et al. 2019).

A third major factor that impacts water quality in these cities is the release of untreated sewage into the waterways either by the rain washing away wastes (as discussed above) or more frequently, the purposeful routing of wastes to streams and rivers (i.e., treating surface waters as “open sewers”). Unfortunately, only around 16% of Addis Ababa's population is connected to the separate sewerage network (Eriksson & Sigvant, 2019) and no sewerage networks exist in Bahir Dar or Hawassa, which leads to a large fraction of the population being dependent on sludge management. This dependence inevitably leads to the release of raw sewage into waterways. Furthermore, in 2012, about 72% of Addis Ababa residents lacked access to adequate toilet facilities (Getachew, et al., 2021), with 6% of urban residents in Ethiopia still practicing open defecation in 2015 (The World Bank, 2017). Ultimately, this leads to unregulated waste discharge from residential areas, adding to water pollution. Specifically, the discharge of human waste leads to water contamination from microbes, disease vectors, and nitrogen-containing compounds, which ultimately spreads disease and causes eutrophication.

Lastly, a fourth major factor impacting water quality, at least locally in the study cities, is the disposal of solid waste. Each of the three cities generates large amounts of solid waste without adequate waste management facilities. For example, in Addis Ababa, only about 70% of the solid waste generated is properly collected and brought to a disposal site. As such, waste often gets piled up and washed off into rivers (Getachew, et al., 2021). Unfortunately, in addition to household and municipal wastes, this solid waste often also includes medical waste, which can pose a health hazard since it is often contaminated with blood and other body fluids (Yohannes & Elias, 2017). Furthermore, even solid waste that gets brought to a disposal site can leach into the water supply.

Surface waters

Surface waters are among the water sources most susceptible to pollution since they are easily accessible and are frequently used for various purposes. While it's important to identify the factors that affect water quality for pollution mitigation, it is also necessary to understand the current state of water quality. The data available on surface water quality in Addis Ababa, Bahir Dar, and Hawassa indicates that these water bodies are substantially polluted.

As discussed above, industrial effluents contribute significant organic pollution to the waterways in Addis Ababa. A study by Getachew, et al. showed that industrial wastewater, human wastewater, and leachates from the city's solid waste disposal sites are considered highly contaminated (Getachew, et al., 2021). These contaminated waste streams then enter waterways where they reduce the overall water quality. For example, high BOD concentration indicates high levels of organic waste and bacteria, which then in turn go on to deplete oxygen and impact aquatic life. Various studies of physicochemical measurements for several streams and rivers throughout Addis Ababa (Table 8) illustrate that for many of these streams, COD, BOD, and DO values fall outside of the acceptable ranges, especially in the dry season when these organic pollutants from point sources do not get diluted by rain and stormwater. Nutrient pollution (phosphorus and nitrogen), often stemming from raw sewage, agricultural runoff, and other solid waste streams, can also lead to significant eutrophication.

The data in Table 8 and other studies (Gizaw, et al., 2004) suggest that all sites measured display extensive signs of eutrophication, since nitrogen and phosphorus contents are high in all samples. In addition, studies in the Addis Ababa area found that biological indicators – both diatoms and macroinvertebrates – show significant ecological quality deterioration (Awoke, et al., 2016; Degefu, et al., 2013), especially as water pollution gets worse. This deterioration generally manifests in a decrease in diversity of organisms, a decrease in the presence of sensitive taxa, an increase in the presence of pollution-tolerant taxa, and other indices. In addition, such ecological deterioration can be accelerated by invasive species, like water hyacinth, that can afflict stagnant bodies of water such as the Aba-Samuel Reservoir. Lastly, contamination with pharmaceutical compounds is also of significant concern, as exposure to these compounds can affect human and ecosystem health. A recent study showed that Addis Ababa is the third-worst city in the world (of the cities studied) when it comes to pharmaceutical pollution, with cumulative concentrations of active pharmaceutical compounds measured at above 50 mg/L (Wilkinson, et al., 2022).

Table 8. A sample of physicochemical measurements throughout Addis Ababa

Site	EC *µS/cm*	TDS *mg/L*	TSS *mg/L*	PO_4-P *mg/L*	NO_3-N *mg/L*	NO_2-N *mg/L*	COD *mg/L*	BOD_5 *mg/L*	DO *mg/L*	Turb. *NTU*	pH	Ref
Little Akaki – Dry Season Mean (Median, Range)	1174 (1290, 465-1705)	581 (636, 225-877)		5.1 (5.1, 0.36-14.5)	0.6 (0.39, 0.03-1.8)	0.11 (0.08, 0.01-0.35)	986 (1046, 311-1697)	216 (129, 60.1-582)	1.6 (0.88, 0.1-5.8)		7.2 (7.2, 5.6-7.7)	(Angello, Tränckner & Behailu, 2020)
Kebena Watershed – Wet Season	444.50	255	101.4	0.55 (Tot. P)	6.30 (Tot. N)		63.00	25.28			6.23	(Asnake, Worku & Argaw, 2021)
Kebena Watershed – Dry Season	1801.19	900	156	8.24 (Tot. P)	75.86 (Tot. N)		99.73	64.63			7.87	(Asnake, Worku & Argaw, 2021)
Little Akaki – Dry Season				20.97	1.31	2.74			3.16	35	7.94	(Adugna, et al., 2019)
Little Akaki – Wet Season				8.92	2.05	10.26			10.26	661	8.27	(Adugna, et al., 2019)

Note: Values highlighted in red are outside of the acceptable range of either the international or Ethiopian standard, whichever is more stringent. The full data set is shown in Appendix A.

Similarly, the picture in Lake Hawassa resembles that of Addis Ababa. Studies (Table 9) indicate that the Lake Hawassa watershed is highly polluted, with many of the measured values exceeding international and Ethiopian guidelines. This contamination, especially the low dissolved oxygen (DO) values measured in many of the samples, makes these waters fairly inhospitable to aquatic life. Furthermore, as is the case in Addis Ababa, the excess nutrients that end up in the watershed lead to eutrophication. Detailed studies (Lencha, Tränckner & Dananto, 2021; Menberu, Mogesse & Reddythota, 2021) show that Lake Hawassa, according to several metrics, is considered in some state of eutrophication. In fact, one of these studies showed that Lake Hawassa's water is unsuitable for drinking, aquatic life, and recreational purposes, and is only suitable for irrigation (Lencha, Tränckner & Dananto, 2021). However, this study did not consider heavy metal pollution. In addition, studies in the Lake Hawassa watershed suggest that biological indicators, both diatoms and macroinvertebrates, show significant deterioration of ecological quality (Mereta, et al., 2020; Fetahi & Mengistou, 2014), especially around areas where industrial effluent enters the lake. In the studies conducted, several parameters were calculated; they all suggested the ecological quality decreases as water in the watershed moves further downstream toward the lake.

Table 9. A sample of physicochemical measurements throughout the Lake Hawassa watershed

Site	EC μS/cm	TDS mg/L	TP mg/L	NO_3 mg/L	NO_2 mg/L	NH_4-N mg/L	COD mg/L	BOD_5 mg/L	DO mg/L	Turb NTU	pH	Ref
Watershed Rivers	235	118		2.7	0.06	1.2	113	18	5.0	21.5	7.8	(Lencha, Tränckner & Dananto, 2021)
Lake Point Sources	3156	1525		7.5	0.07	7.1	368	107	2.2	15.1	8.3	(Lencha, Tränckner & Dananto, 2021)
Lake Hawassa	853	437	0.32	7.2	0.04	2.3	129	24	4.2	10.7	8.6	(Lencha, Tränckner & Dananto, 2021)
Lake Hawassa dry season	837	407		6.2			200	61	5.2	6.5	8.8	(Menberu, Mogesse & Reddythota, 2021)
Lake Hawassa wet season	806	435		5.8			149	51	5.6	6.1	9.1	(Menberu, Mogesse & Reddythota, 2021)

Note: Values highlighted in red are outside of the acceptable range of either the international or Ethiopian standard, whichever is more stringent. The full data set is shown in Appendix A.

Lastly, for Bahir Dar, Lake Tana does not appear to be as polluted as some of the other bodies of water explored in this study. While the lake would certainly be considered polluted by various organic and nutrient pollution metrics, several of the values are not as drastically above the guidelines as is the case in other regions (Table 10). The main concern presented by these values is the presence of excess nutrients and low dissolved oxygen that make areas of the lake inhospitable to aquatic life. These conditions have moved the lake into eutrophic territory (Goshu, Koelmans & de Klein, 2017), potentially influenced in part by the presence of invasive water hyacinth (Muche, Mucheye & Tadesse, 2020). These parameters are of enough concern to make the water poorly suited for consumption and many other human uses. In addition, biological indicators show some deterioration of ecological quality in the Lake Tana Basin, especially around some industrial effluent sites (Melaku, 2017; Awoke, et al., 2016; Mehari, Gebremedhin & Ayele, 2015). Earlier studies found Lake Tana to be healthy (Imoobe & Akoma, 2008), suggesting that ecological quality has declined over the past decade.

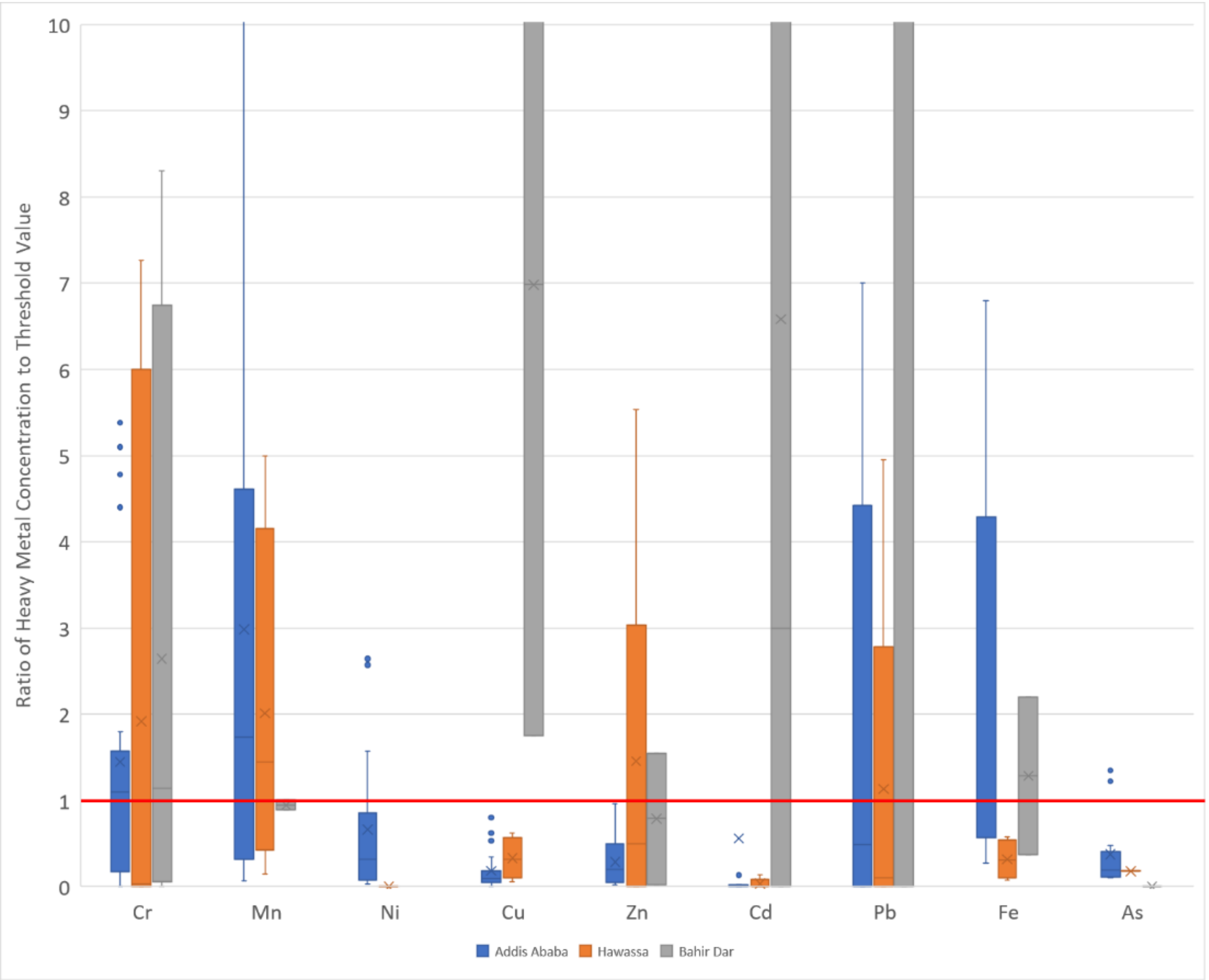
Table 10. A sample of physicochemical measurements throughout the Lake Tana watershed

Site	EC *µS/cm*	TDS *mg/L*	TP *mg/L*	NO_3-N *mg/L*	NO_2-N *mg/L*	NH_4-N *mg/L*	COD *mg/L*	BOD_5 *mg/L*	DO *mg/L*	Turb *NTU*	pH	Ref
Lake Tana	143	94	0.99	0.79					5.99		7.6	(Kassa & Tibebe, 2019)
Lake Tana	335	169									6.5	(Kindie, et al., 2020)
Dirma River	100-1000	40-490	0.04-13.8	0.15-2.42	0.01-1.01	0.03-5.5			2.2-7.2	3.0-1002	6.4 - 8.7	(Goshu, Koelmans & de Klein, 2017)
Garno River	180-633	100-411	0.36-2.4	0.09-2.1	0.0-0.02	0.02-0.5			3.0-4.1	2.1-1002	7.8 - 8.5	(Goshu, Koelmans & de Klein, 2017)
Lake Tana	100-1000	148-178	1	0-3.66	0-0.366	0-12		8.5-226.3	3-7.6	11.2-125	6.8 - 8.3	(Goshu, Koelmans & de Klein, 2017)

Note: Values highlighted in red are outside of the acceptable range of either the international or Ethiopian standard, whichever is more stringent. The full data set is shown in Appendix A.

In addition to organic pollution, pollution with heavy metals is commonly associated with industrial effluent (Berihun & Solomon, 2017) and less commonly also with urban runoff. These heavy metals, while usually present in nature at low background levels, can cause serious harm to the environment and human health when they start accumulating. Measurements of the concentrations of a selection of heavy metals taken in the Addis Ababa metropolitan area (Figure 15) show that almost all of the samples taken were outside of the acceptable ranges set by the WHO and EEPA for at least one metal; these water sources are also largely unacceptable for irrigation due to the risk of these heavy metals accumulating in the soil and in agricultural products.

Figure 15. Box and whisker plot of heavy metal contamination in the three cities studied



Note: Values above 1 are outside of the acceptable range established by the WHO or EEPA, whichever is more stringent. The full data tables are shown in Appendix A.

Lake Hawassa appears to also have significant heavy metal contamination. Studies (Figure 15) show that some values are above the acceptable range (for Cr, Mn, Zn, and Pb), though other forms of heavy metal pollution appear to be less rampant. However, since heavy metal pollution can cause serious harm to the environment and human health, and since heavy metals can accumulate in soils and agricultural products, any of these elevated values are of concern if the water is used for irrigation.

In addition, the Lake Tana watershed also appears to struggle to stay within WHO guidelines for metal concentration (Figure 15). Specifically, the lead and cadmium values measured by one study are of serious concern, as these two heavy metals are highly toxic, and the measured value was far beyond the guidelines. However, on this topic, data was relatively sparse for Lake Tana and another study (Goshu, Koelmans & de Klein, 2017) found very low heavy metal contamination. This large range of values measured is reflected by the very large boxes (which represents the middle two quartiles) for Bahir Dar for several metals in Figure 15. As such, while concern is certainly warranted, further study is needed.

Lastly, water pollution often also leads to the presence of microbes that have the potential to cause disease in humans. Several studies (Mengesha, Asfaw, et al.; 2021; Mulu, Ayenew & Berhe, 2013; Alemayehu,

2001) show that the waterways in the Addis Ababa area are contaminated with total coliform (TC) and fecal coliform (FC). These bacteria are used as indicators of bacterial contamination, suggesting the possible presence of pathogenic bacteria. Studies also confirmed the presence of potentially disease-causing microbes in Lake Hawassa (Daka, Beyene & Dires, 2021; Gorems, et al., 2018; Worako, 2015). In fact, in addition to the presence of total coliform and fecal coliform found by these studies, Daka, et al. also showed the presence of multidrug-resistant pathogenic bacteria. Finally, the presence of potentially disease-causing microbes in Lake Tana was also confirmed by several studies (Goshu, Koelmans & de Klein, 2017; Abera, et al., 2014; Ewnetu, Bitew & Chercos, 2014; Wondie, 2009). In addition to total coliform, fecal coliform, and *E. coli*, one study also found other potentially disease-causing bacteria, many of which exhibit some antibiotic resistance (Abera, et al., 2014). As such, the water in all three watersheds poses a threat to human health when ingested or when used for irrigation, since the bacteria can end up on agricultural products.

Overall, eutrophication and contamination of waterways in the Addis Ababa area and Lake Hawassa with various organic, inorganic, and microbial pollutants, make the surface water in the cities largely unfit for human consumption, irrigation, and other human uses. Additionally, given that Lake Hawassa is topographically closed, rehabilitation of the lake will be much more difficult and a much lengthier process, since there is no outflow that can carry pollutants away. In contrast, while Lake Tana overall is likely not as polluted as the other two watersheds, it's still in a mesotrophic or eutrophic state, and contamination with various pollutants makes the surface water largely unfit for human uses. Maintaining water quality in Lake Tana is not only important for the surrounding communities, but since it is at the head of the Abbay River / Blue Nile, a major tributary of the Nile River, Lake Tana's pollution has far-reaching consequences for downstream communities as well. As such, all three watersheds need a strong pollution mitigation program.

Groundwater

Groundwater plays an important role in Ethiopia's water supply. It is the main source for domestic water supply in many areas, especially in the country's drier regions such as Somali (Smedley, 2001). As mentioned in the introduction, Ethiopia has aquifers that vary highly in productivity and water quality. The three cities that are the focus of this study are all located in areas with fairly high aquifer productivity, meaning groundwater is a reliable source of water in these areas. Unfortunately, data on groundwater quality across Ethiopia is sparse. Groundwater quality is measured using the same types of indicators as for surface waters, though salinity is a greater concern. Overall, groundwater quality is highly variable, ranging from fresh water to more saline waters. The parameters of major concern for groundwater are salinity, total dissolved solids (TDS), fluoride, iodine, nitrate, heavy metal contamination, and bacterial contamination. There is also generally a concern that pollution from anthropogenic activities, such as agricultural runoff, leachate from solid waste, and seepage of fecal sludge, can endanger groundwater resources (Abiye, 2008). This pollution can lead to human health hazards, especially since, in addition to heavy metals and pathogens, high levels of nitrates also pose a health risk (Rahman, et al., 2020; Wagh, et al., 2020).

In general, Addis Ababa gets a large fraction of its water supply from groundwater, with the main groundwater potential areas located in the eastern and southern parts of the city. In Addis Ababa, the major sources of pollution of concern for groundwater are residential waste and run-off from industries and businesses, such as garages and fuel stations (Abiye, 2008). From a chemical perspective, the dominant ions in the city's groundwater are sodium and calcium (Abiye, 2008). However, there is also a significant presence of chloride ions, nitrate, and phosphate, which suggests potential seepage of contaminated water from the rivers or surface runoff (Tegegn, 2012; Abiye, 2008; Abay, 2008). Furthermore, there are concerns that wastewater infiltrates into groundwater without sufficient distance and time to filter out pollutants. This contamination often comes from septic tanks, latrines, or defective sewerage lines located too closely to poorly constructed wells (Abiye, 2008; Engida, 2001). In addition, one study found high levels of lead (Awoke, et al., 2016) in groundwater samples from Addis Ababa and another study found high chromium and cadmium levels (Demlie & Wohnlich, 2006). Overall, the shallow groundwater in the city center is unsuitable for consumption, driven largely by pollution of surface water (Abiye, 2008). While some of this data is over 10 years old, the deteriorating surface water quality suggests that groundwater pollution is unlikely to have improved. As such, pollution management for surface waters will yield additional benefits in protecting shallow groundwaters. On the bright side, in addition to potentially drilling deeper wells, a recent study (Tsegaye, 2021) found that groundwater quality rapidly improves as distance increases from the city center, suggesting that the area overall has fairly clean groundwater.

In Hawassa, one of the main concerns for groundwater quality is the presence of high fluoride concentrations, due to the rock formations in the Rift Valley area. Concentrations greater than 10 mg/l are not uncommon (the WHO guideline value is 1.5 mg/l) (Smedley, 2001). High fluoride concentrations can cause skeletal and dental fluorosis after long-term use of contaminated drinking water. One recent study, however, found Hawassa's groundwater quality close to meeting the WHO guidelines for consumption, though the water was a bit high in manganese, phosphorus, and alkalinity (Meka & Gemechu, 2018). Some of these pollutants could come from anthropogenic activities, since polluted Lake Hawassa does interact with the groundwater system (Eromo, 2011). Interestingly, the boreholes studied around Hawassa were all in compliance with the WHO guidelines with regards to fluoride. On the other hand, another study showed that shallow wells are overwhelmingly susceptible to high fluoride and TDS concentrations (Abdurahman & Zewdie, 2018). This also illustrates that deeper boreholes have a much lower risk of fluoride problems. Overall, while groundwater from deep boreholes does not appear to suffer from as much contamination as surface waters in Hawassa, it still requires regular monitoring and may need treatment before consumption.

In Bahir Dar, groundwater serves as a major source of fresh water for the fast-expanding population in the Lake Tana basin, as evidenced by the fact that about 71% of the water supplied by the public utility is groundwater (Nigate, et al., 2017). However, when tapping groundwater, the city must consider the complex hydrogeology of the Lake Tana basin, as there are areas in the basin that yield unusually saline water. Understanding water quality in the basin is vital for providing a high-quality water supply. A recent study (Bawoke & Anteneh, 2020) used GIS techniques to better understand groundwater quality in the basin, specifically the Andasa watershed. It found that there are large areas of good- and excellent-quality water in the basin, but that water quality gets significantly worse (due to issues such as high nutrient content) closer to disposal landfill sites, irrigated areas, and urban centers, suggesting that pollution from anthropogenic activities is impacting groundwater in those areas. Furthermore, other studies (Wondie, 2009; Goshu, 2007) explored the microbial fecal indicators of the groundwater in Bahir Dar and found that most samples were contaminated with total coliform, *E. coli*, and *Clostridium perfringens*, though pathogenic potential was not evaluated. This contamination is likely due to seepage of wastes from poorly constructed septic tanks. One of these two studies also confirmed elevated levels of nutrients in the groundwater. Overall, the Lake Tana basin has areas with groundwater of good quality; however, the aquifers have certainly been influenced by human activities, and careful management is necessary to prevent further degradation of water quality.

Drinking water supply system

In Ethiopia, 93% of urban households have access to an improved source for drinking water, and 56% have piped water on the premises (The World Bank, 2017). Piped water faces the water quality concerns discussed above and requires appropriate treatment by the water utility. But the water distribution system itself is also a potential source of contamination due to aging, cracked, or leaky supply pipes. Contamination becomes of special concern when the water supply is intermittent and water remains stagnant in pipes on a regular basis, as is the case in Addis Ababa. In Addis Ababa, piped water is treated to drinking water standards before being sent into the distribution network. However, unfortunately, a study in Addis Ababa showed that a significant proportion of food establishments (26.4% in the wet season, 10.7% in the dry season) suffer from water supply contaminated with *E. coli* (Girmay, et al., 2020). While this study did not establish whether this contamination is coming from the distribution network, the contamination itself is already of concern, since these samples were from licensed food establishments. A different study specifically looked at the impact of the water distribution system in Addis Ababa. It found an increase in conductivity, turbidity, zinc, and iron, and a decrease in residual chlorine when comparing treated water leaving the treatment plant with water out of a household tap (Mekonnen, 2015). Furthermore, this study also confirmed that no *E. coli* or total coliform bacteria were present in the treated water at the treatment plant, but that a significant portion of samples from household connections contained these bacteria. The detection of bacteria especially increased after a supply interruption and reinstatement event. Occurrence also increased in the rainy months, suggesting intrusion of contaminants. Similarly, in Bahir Dar, a study also found a significant increase in *E. coli* and total coliform bacteria going from water reservoirs to the household tap (Abera, et al., 2014). To our knowledge, a similar study for Hawassa has not been done; however, it stands to reason that it would find similar problems. Overall, there is an urgent need for Ethiopian cities to invest in their water distribution networks, as it also represents a source of water pollution for individual households.

Sanitation

In addition to the water supply network, the sanitation network is an important lever for communities to control and manage pollution. As mentioned earlier, inadequate sanitation is a major contributing factor to surface and groundwater pollution. In 2015, only 27% of the population in urban areas had access to improved latrines (The World Bank, 2017). Instead, more than 60% of the population uses traditional latrines. These latrine pits are often of poor design and quality, with the fecal sludge often dumped directly into water bodies, storm drains, or simply into an open space in the environment. This indiscriminate disposal of fecal sludge then exposes residents to significant health hazards, such as the 2016 cholera outbreak (The World Bank, 2017). Rates are also generally worse in marginalized and displaced communities (WHO & UNICEF, 2021). In addition, as discussed above, Addis Ababa is the only city in the country with a sewerage network; however, it serves less than 20% of the city's population (Eriksson & Sigvant, 2019; The World Bank, 2017). Unfortunately, this lack of sewerage networks then leaves almost everyone reliant on unreliable desludging services. This context explains why fecal contamination of water sources is so common and illustrates the pressing need to implement functioning sanitation services.

4.3 Health impacts of water pollution

In addition to the environmental and ecological impacts of water pollution discussed above, water pollution also threatens human health. One health risk already mentioned is the presence of potentially disease-causing pathogens in drinking water. In all three study cities, a significant number of drinking water sources have been found to be contaminated with total coliform and *E. coli*, both of which are indicators of fecal contamination. Some contaminants have also been found in the urine and blood of affected people (Yard, et al., 2015), and water pollution can also impact human health through the food system.

Specifically, some pollutants, such as heavy metals, can bioaccumulate in aquatic species, such as fish, and in agricultural products irrigated with contaminated water. Several studies covering the Akaki river catchment, Aba-Samuel Reservoir, Lake Hawassa, and Lake Tana illustrated the potential bioaccumulation of a whole range of heavy metals (As, Cd, Cr, Pb, Zn, Fe, and Hg) in fish, though in most samples, the concentrations in fish muscles were still within the WHO limits (Kindie, et al., 2020; Kassegne, et al., 2019; Kassegne, et al., 2018; Dsikowitzky, et al., 2013). Only one study on Lake Tana found a few samples that exceeded the acceptable concentration of heavy metals (Kindie, et al., 2020). Overall, however, these studies illustrate the potential hazard bioaccumulation can pose to a vital food source.

In addition, the bioaccumulation of heavy metals and contamination with pathogens can occur in agricultural produce irrigated with contaminated water. Studies in Addis Ababa clearly show that vegetables can bioaccumulate toxic heavy metals to levels beyond the recommended guideline values (Aschale, Sileshi and Kelly-Quinn, 2019; Mengesha, Kidane, et al., 2017; Weldegebriel, Chandravanshi & Wondimu, 2012; Gebre & Van Rooijen, 2009). While none of these studies goes on to explore the bioavailability of these contaminants, some studies explore indices to show that a health hazard does exist (Mengistu, 2021; Aschale, Sileshi & Kelly-Quinn, 2019). However, independently one study (Yard, et al., 2015) did attempt to understand accumulation of heavy metals in the human body by analyzing blood and urine samples and comparing two groups, of which one was living closer to a contaminated water source. While the study clearly found that those living closer to a contaminated source had higher levels of heavy metals in their bodies, it was unable to directly link these levels to an exact contamination source. Overall, these findings raise concerns about accumulative health impacts. The actual bioaccumulation of these heavy metals in Ethiopia's population would be an important area for further study.

Furthermore, farmers are exposed to these heavy metals particularly via dermal contact and inhalation while tending their fields, compounding their exposure, and increasing their associated health risk (Mengesha, Kidane, et al., 2017). A detailed study also showed that vegetables can be highly contaminated with coliforms and therefore unsafe for consumption (Mengesha, Asfaw, et al., 2021). In fact, vegetables irrigated with contaminated water have been observed to be responsible for outbreaks of various diseases, such as cholera, typhoid, and dysentery (Eriksson & Sigvant, 2019). As such, there is an overwhelming need to provide irrigation water that does not pose a health concern for those producing and consuming agricultural products.

Lastly, pharmaceutical pollution, as that documented in Addis Ababa (Wilkinson, et al., 2022) can have a significant health impact by, among other things, encouraging the emergence of antibiotic-resistant bacteria.

Overall, water contamination and the associated effects discussed in this section point to a risk of significant disease burden caused by water pollution. Several global studies illustrate how inadequate drinking water and sanitation is linked to diseases such as diarrheal diseases, typhoid, cholera, hepatitis, dysentery, and schistosomiasis (Prüss-Ustün, et al., 2019; Hendrix, 2012). In addition, two studies in Addis Ababa demonstrate the high incidence of these types of diseases. First, one study in Lafto Sub-city found that 24.8% of the population suffered from a solid waste and sanitation-related disease in 2008—5.8% had intestinal parasites; 4.5% common diarrhea; 3.7% respiratory infection; 2.9% amoeba; 2.7% typhoid fever; 2.6% typhus; and 2.6% dysentery (Mazhindu, Gumbo & Gondo, 2012). Another study showed that in 2005 Addis Ababa had over 14,000 annual cases of typhoid fever, almost 9,000 cases of diarrhea with blood, over 10,000 cases of diarrhea with severe dehydration in children under 5, and that diarrheal diseases caused 89 deaths in the city, with a particularly high incidence in children (Gebre & Van Rooijen, 2009). Lastly, the same study further showed that the incidence of diarrheal diseases nationally jumps to well over 200,000 cases annually. However, as the numbers used by Gebre & Van Rooijen are official Ethiopian Ministry of Health counts, the actual incidence of sanitation-related diseases is likely much higher.

We estimate the impacts of inadequate WASH on health in Addis Ababa based on data derived from the Global Burden of Disease (GBD) study of the IHME (IHME, 2020). These impacts are quantified in relation to five health outcomes: diarrheal diseases, lower respiratory infections, protein-energy malnutrition in children under five, malaria,[6] and schistosomiasis.[7] We compute these effects as follows: for the diarrheal diseases and lower respiratory infections, we use the premature death rate (deaths/100,000 people) and morbidity rate (YLDs/100,000 people) due to inadequate WASH, drawn from the GBD study for Addis Ababa and the city's population in 2019 (4.6 million people)[8]. For the other health outcomes, we use the disease-specific premature death and morbidity rates for Addis Ababa from the same study, and the proportions attributable to inadequate WASH provided by Pruss-Ustun et al. (2019) for protein-energy malnutrition (17%), schistosomiasis (46%), and malaria (80%).

Based on this information, Table 11 illustrates the health effects of inadequate WASH in terms of average values and intervals of uncertainty. It shows that inadequate WASH was responsible for about 725 premature deaths. Diarrheal diseases and lower respiratory infections account for nearly 95 percent of the total. Moreover, children under five are the most affected group, representing 17 percent of the premature deaths related to WASH (Figure 16). In terms of morbidity, inadequate WASH was responsible for about 6,710 YLDs in the city, as shown in Table 11. Chapter 6 provides an economic valuation of these impacts. Further studies are recommended to better understand the prevalence of these diseases in other urban areas of the country, such as Bahir Dar and Hawassa.

Table 11. Impacts of inadequate WASH on health in Addis Ababa (2019).

	Unit	Average*	Lower bound	Upper bound
Mortality				
Diarrheal diseases	Number deaths	467	193	807
Lower respiratory infections	Number deaths	219	97	350
Protein-energy malnutrition (< 5 year old)	Number deaths	3	1	5
Schistosomiasis	Number deaths	0	0	1
Malaria	Number deaths	35	2	156
Total	Number deaths	**725**	**293**	**1,318**
Morbidity				
Diarrheal diseases	Number YLDs	5,476	3,590	7,841
Lower respiratory infections	Number YLDs	57	25	100
Protein-energy malnutrition (< 5 year old)	Number YLDs	396	247	578
Schistosomiasis	Number YLDs	0	0	0
Malaria	Number YLDs	781	574	1,030
Total	Number YLDs	**6,710**	**4,435**	**9,549**

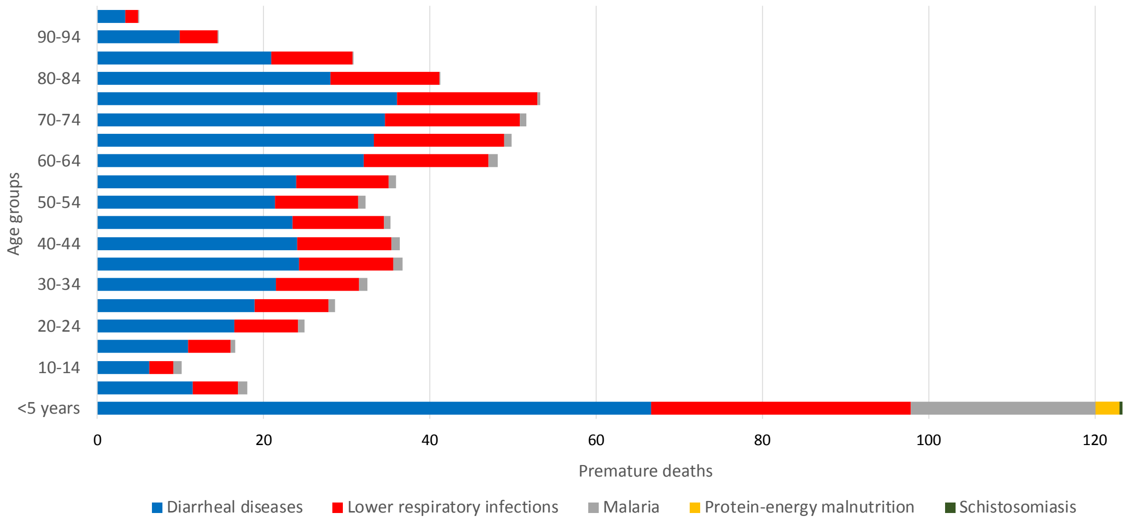
*Sources: IHME (2020) for the mortality and morbidity rates; Pruss-Ustun et al. (2019) for the proportions of cases of protein-energy malnutrition (17%), schistosomiasis (46%) and malaria (80%) attributable to the inadequate WASH in Sub-Saharan Africa. https://worldpopulationreview.com/world-cities/addis-ababa-population for the population in Addis Ababa. * median value. Totals might not add up exactly due to rounding.*

[6] For this disease, we estimate the health impacts of insufficient management of the water resource, related to lack of cleaning and maintenance of drains, failure to eliminate stagnant water bodies, and the establishment of dwellings close to transmission vectors.

[7] Schistosomiasis can occur when people contact water containing certain aquatic snails that have been infested with parasitic worms (Pruss -Ustun et al., 2019).

[8] https://worldpopulationreview.com/world-cities/addis-ababa-population

Figure 16. Premature deaths due to inadequate WASH in Addis Ababa, by age group.



Source: Authors, based on data from IHME (2020)

4.4 Gaps and Needs for Improvement

Overall, the study identified several gaps and some simple measures that could be quickly taken to combat water pollution. These gaps can be grouped into three categories.

Point-source pollution

First, industrial/commercial point-source pollution should be addressed. The nature of point sources means that often only a small group of actors (such as industrial plants) must be brought into compliance with effluent treatment requirements. On that front, Ethiopia already has various regulations addressing industrial effluents. However, these regulations are poorly enforced (Awoke, et al., 2016). As such, the first step should be to understand why enforcement of and compliance with the existing regulations is poor and how it can be improved, which by itself would have a meaningful impact on pollution. This lack of enforcement could be due to a variety of reasons, including that the regulations are too arduous, in which case it may be worth reexamining them. After stepping up enforcement, regulations should then again be reexamined for how effective they are at preventing the release of pollutants and should then be adjusted appropriately.

Water pollution due to waste

The second bucket would be water pollution due to solid and hazardous waste. Solid waste pollution is, to an extent, a mix of point sources (big landfills) and non-point sources (solid waste discarded in the environment). A potential first step to address water pollution from solid waste would be to ensure that landfills and dedicated solid waste disposal sites are located and constructed so that wastes cannot leach into the water supply. Beyond improving existing disposal sites, further measures are likely needed to better manage solid waste generated in these three cities, as there must be an effort to address solid waste being improperly disposed in the environment. For example, solid and hazardous waste management by small businesses (such as car mechanics) and households will be important for reducing urban run-off. This effort will likely require a mix of regulations and education campaigns. Further details with regards to solid waste management can be found in Chapter 5.

Non-point sources

The last category is made up of the remaining non-point sources. These are quite hard to combat because they are driven by a large number of actors and are not concentrated in a single area. However, addressing them remains vital to reducing pollution. The biggest impact on non-point source pollution would likely be from improvements in sanitation. This would include elimination of open defecation, ensuring that latrines are placed sufficiently far away from wells and groundwater, and improving the management of fecal sludge. Several programs to improve sanitation are underway, including some conducted by the World Bank; however, significant further improvement needs to be made to see reductions in pollution. It will also be important to ensure that farms use measures that prevent agricultural run-off, especially since many measures that prevent agricultural run-off also prevent the loss of topsoil from farms and should thereby improve agricultural output. This effort will also likely require a mix of regulations and education.

While point sources may be a good place to start, it is important for the government to address pollution sources in all three categories to achieve a significant improvement in water quality. Addressing all three categories in parallel may be possible, because the different pollution sources mostly lie in the purview of different institutions and agencies. However, the involvement of many agencies may also make a coordinated effort more complex and complicated. As a whole, a significant government commitment is required to see improvements in water quality. However, the rewards are significant, as can be seen in the sections discussing the economic, environmental, and health costs of polluted water.

Management and monitoring

In addition to addressing the sources of pollution, it will be important to strengthen water resource management and monitoring and ensure that distribution networks are of sufficient quality to prevent water contamination during distribution. Currently, only three river basins (Awash, Abbay, Rift Valley Lakes) in Ethiopia (Nigussie, et al., 2020) have dedicated water resource management authorities while the remaining nine river basins are managed by a patchwork of authorities. As such, creating dedicated authorities to ensure adequate resource management and water monitoring would further assist in improving water quality by decreasing institutional complexity and collecting data that can be used as a basis for further pollution reduction regulations and interventions. Overall, the government of Ethiopia has multiple options to address their water pollution problem, and while achieving good water quality will take time, it is within reach.

Chapter 5 Solid Waste

This chapter analyzes the current situation of SWM in the three study cities, assesses the impacts of SW and SWM on the environment and economy, and then discusses the challenges and gaps in SWM and the needs for improvement.

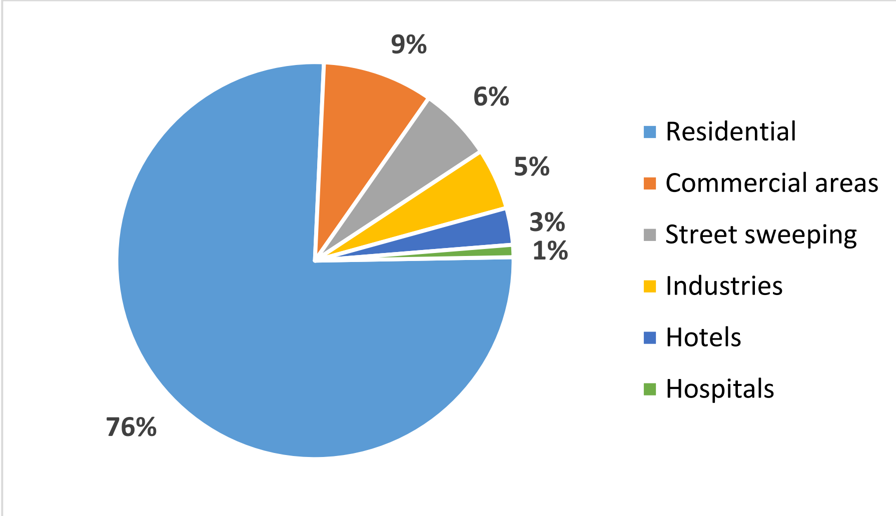
5.1 Overview of SWM situation in Addis Ababa, Bahir Dar and Hawassa

Solid waste generation, sources, and flow of waste streams

Around 70% of Ethiopia's total solid waste (SW) is generated in cities and urban areas (Tassie et al., 2019). The World Bank (Kaza, 2018) estimated the municipal solid waste generation rate in Ethiopia to be 6 million tons per year in 2015. This rate is projected to rise to 10 million tons per year by 2030. SW data is lacking in Ethiopia. In Addis Ababa, the only available data is the SW volume measured daily at the entrance to the Reppie Landfill and Waste-to-Energy facility (plus the volumes of fly ash and bottom ash that are byproducts of the waste-to-energy facility). Ethiopia's daily per capita SW generation varies from city to city, and between urban and rural areas. Though Addis Ababa is a particularly economically productive city, accounting for about 8% of the national GDP, its daily SW generation rate is estimated at 0.67 kg per capita, comparable to Bahir Dar's 0.56 kg/capita/day and Hawassa's 0.43 kg/capita/day (Xie & Mito, 2021; UNHABITAT, 2021; USAID, 2015). As the living standards in these cities continue to improve, daily per-capita waste generation will presumably continue to increase.

Households, commercial areas, industrial activity, hotels, and street sweeping are the major sources of SW generation in Ethiopian cities. According to the Addis Ababa Sanitation Management Agency (2019), the biggest producers of municipal solid waste in Addis Ababa are households and small businesses in residential areas. They contribute 76% of the total municipal SW, followed by commercial areas (9%), streets (6%), and industrial activity (5%), as shown in Figure 17. Similarly, in Bahir Dar, households accounted for around 70% of SW generation. In Hawassa, however, households account for only 35%, with the majority of municipal SW generation originating from large institutions and industry. This discrepancy suggests that, to some extent, the share of SW sources is unique to each city in Ethiopia. It is necessary to note that SW generation data is under-reported across the country and reporting methods are inconsistent, making the city-to-city comparisons challenging.

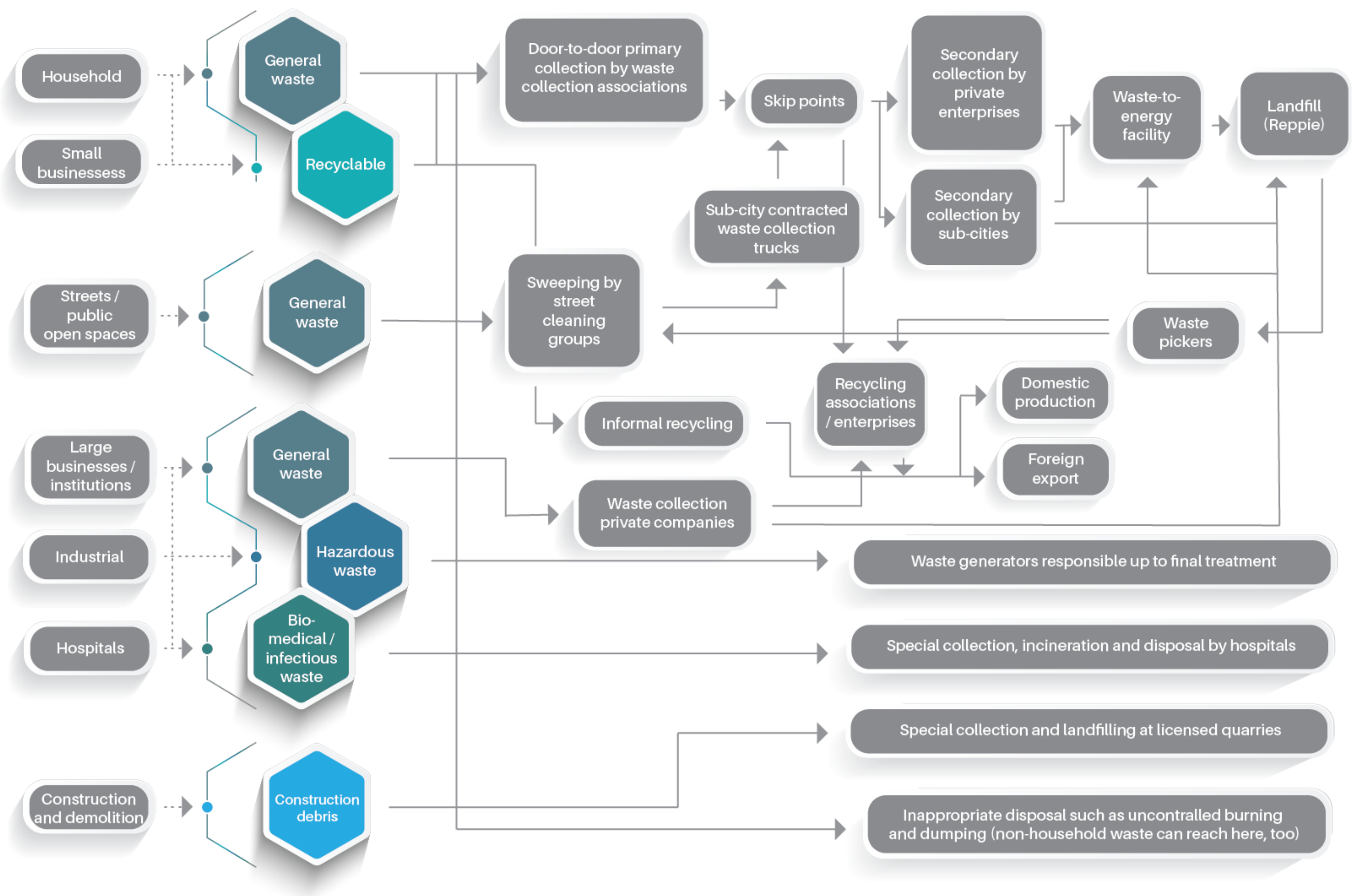
Figure 17. Share of municipal solid waste by source in Addis Ababa in 2019



Source: Addis Ababa Sanitation Management Agency.

The general flow of waste in Addis Ababa is depicted in Figure 18, demonstrating the paths of various SW streams from each source through to collection, transportation, recycling, and final disposal facilities. The primary collection of SW from households and streets and transfer to waste collection points (or "skips") is conducted by waste collection associations managed by the SWM office of sub-cities or districts. Then companies responsible for secondary collection take waste from skips and transfer stations and transport it to the Reppie Landfill or adjacent Reppie Waste-to-Energy facility. Large businesses and institutions, industrial sites, and hospitals are responsible for their own SW, and they normally contract private companies to directly collect and transport their non-hazardous SW to the Reppie site. Construction waste generators are also required to handle their debris properly and have it transported and landfilled at licensed dump sites. Only a small proportion of waste is collected and sorted by small-scale associations, private enterprises, or informal collectors to extract recyclables that are resold for domestic production or export. Aside from the above arrangements, which are largely under the government's purview in districts, sub-cities, and municipalities, there are also informal systems where private entities or individual waste pickers collect SW, sort and recover recyclable materials, and dispose of the rest in illegal open dumpsites. About 50% of the SW transported to the waste-to-energy facility in Addis Ababa is incinerated. The rest is landfilled.

Figure 18. The flow of waste streams



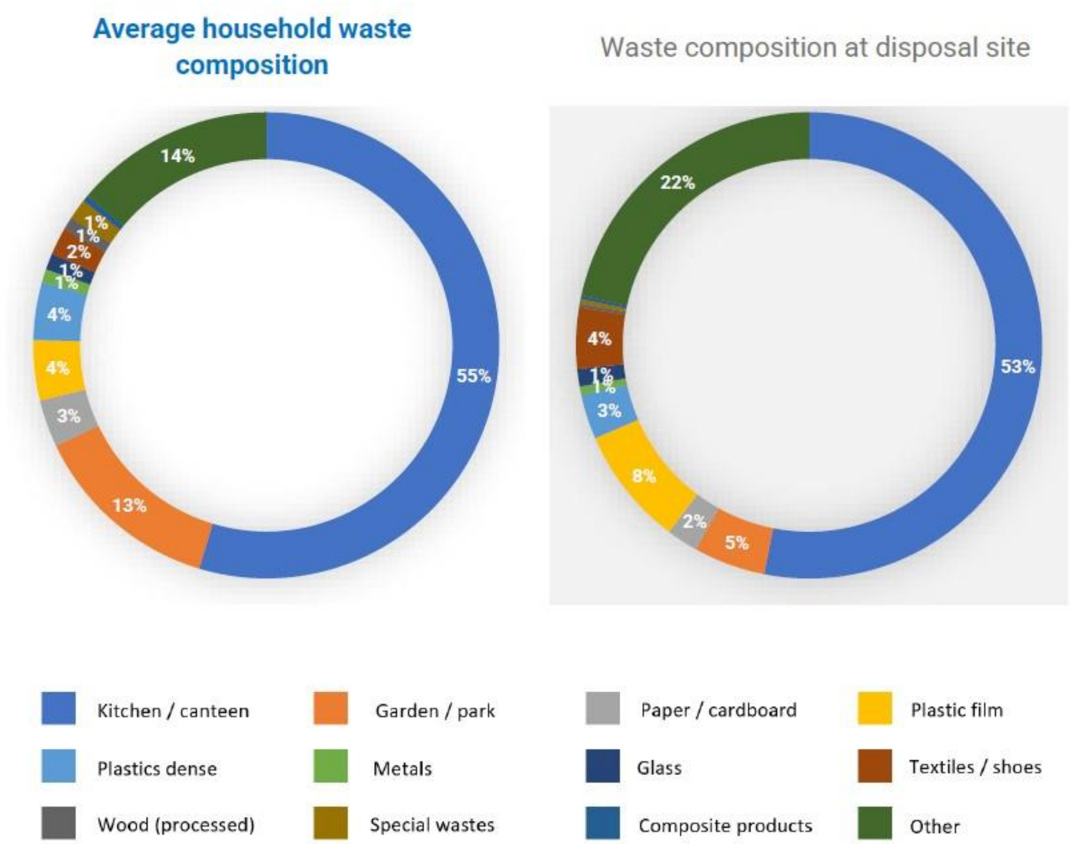
In Bahir Dar, some informal collection occurs but most municipal SW is collected by five micro and small enterprises (MSEs) and one private company, all of whom are employed by the municipality. The collection is done door-to-door once per week. The collected SW is brought to communal transfer stations sited at the edge of main roads for accessibility. These roadside collection sites do not take many measures to protect waste from the impacts of rain and sun and can create environmental, health, and aesthetic issues. The waste is then transferred to the Bahir Dar landfill.

Similarly, in Hawassa, waste collection and transportation are primarily conducted by private associations and informal workers who use donkey carts to do door-to-door collection from households, institutions, and commercial centers. There are no WtE facilities in Bahir Dar or Hawassa; most of the cities' SW is landfilled and the rest is littered or openly burned.

SW composition

The disposal process of generated waste depends not only on the source of waste, but also its composition. The composition of waste in most Ethiopian cities is largely unknown due to the lack of reliable data on waste generation. Luckily, UN-Habitat applied its Waste Wise Cities Tool (WaCT) to Addis Ababa in 2021. It surveyed the composition of both household waste and the waste disposed at landfill. The survey results (shown in Figure 19) indicate that kitchen waste comprises 55% of household waste, plastic waste 7-8%, and paper 3% (UN-Habitat, 2022). Similar surveys done by UN-Habitat in Bahir Dar conclude that 44% of household waste is kitchen waste, 11% is plastic waste, and 4% is paper (UN-Habitat, 2021).

Figure 19. Composition of waste at the households and at the landfill in Addis Ababa, 2021



Source: UN-Habitat, 2022.

SW collection and transportation

Little reliable information on SW collection rates is available for Ethiopia. The collection rate in Addis Ababa is estimated to be about 70% (Xie & Mito, 2022), which compares favorably to the 48% average collection rate of peer cities in low-income countries. The percentage of solid waste collected in Bahir Dar and Hawassa was reported to be 81.3% and 80.8%, respectively (MUDI, 2020). This indicates that a range from 20-30% of SW was left uncollected in these cities. There is evidence of this uncollected SW being dumped illegally in river channels, drains, roads, and open spaces or being openly burned. Challenges for SW collection in these cities include an insufficient number of vehicles for primary and secondary collection, inappropriate kinds of waste management vehicles, and low frequency of SW collection trips.

SW Recycling

Ethiopia's municipal solid waste includes various recyclable materials. UN-Habitat's WaCT surveys conclude that 40-50% of household waste is recyclable. However, recycling is insignificant in Ethiopia largely due to the lack of waste separation. Waste separation at the houshold level is rare and sporadic. The most consistent recycling practices come from informal recyclers who remove specific materials with re-sale value from the waste stream. For example, the city of Addis Ababa hasn't regulated municipal SW source separation, leading to large amounts of recyclable waste ending up in landfills. Throughout different waste collection stages, limited separation efforts occur at sources, skip points, transfer stations, the Reppie Landfill, and other dump areas. There are several groups of recyclers that separate and recycle waste: informal (and mostly homeless) waste pickers (or "street boys"), the korales (or Qoralés, working-class recyclers), private enterprises, and additional waste pickers at the municipal dumpsite (also called "scavengers"). The "street boys" and korales are mainly active in door-to-door waste collection. Small-scale private enterprises and the informal sector mainly separate recyclable materials at skips. "Scavenger" waste pickers recycle at the landfill (Tassie et al., 2019; Alemu, 2017; IGNIS, 2014). Despite an increase in recycling business revenue, the Addis Ababa Sanitation Management Agency (2019) estimated that the total volume of recycled waste is less than 5%.

In Hawassa, the involvement of institutions and associations in the recycling of waste – namely Community Initiatives Facilitation and Assistance, Hawassa Webet Plastic Recycling Association, and Green REE Business – has led to recycling rates as high as 19%. Moreover, Hawassa has municipal SW composting practices that account for 2% of waste volume. Bahir Dar has a composting facility which was constructed with the support of a GEF Nationally Appropriate Mitigation Action project and has been operating for several years. The city also has limited recycling activities carried out by informal waste collectors (UNEP, 2010). However, the city's recycling rate is very low and barely reported.

Waste to Energy

One waste disposal process in Ethiopia unique to Addis Ababa is its Reppie Waste-to-Energy (WtE) facility, which is owned by Ethiopia Electric Power. The WtE is built next to Reppie landfill and generates 25 MW of electricity. With a total capital investment of about US$120 million, this facility is the first of its kind in Sub-Saharan Africa. It serves a dual purpose by greatly reducing the total amount of waste that enters the landfill and by providing electricity. It incinerates around 1,400 tons of SW each day and has the capacity to provide over 185 GWh of electricity to the Ethiopian national grid annually. Of the SW that arrives to the WtE facility, about 80% is burned, leaving about 3% as fly ash and 17% as bottom ash to be landfilled. Overall, the facility has allowed for an approximately 60% reduction in SW dumped at the landfill. The Reppie WtE facility can play a critical part in the future of Addis Ababa's solid waste management, as it could prevent as much as 1,200 tons of waste from being dumped in the landfill daily.

However, with the facility still being in its early stages of operation, uncertainty remains surrounding its financial sustainability, technical reliability, as well as its environmental performance.

Landfill

Despite the operations of the Reppie WtE facility, landfilling remains the main method of SW disposal in Ethiopia. Addis Ababa will continue to rely on landfilling, including the Reppie landfill, to dispose of the SW that WtE cannot process. Bahir Dar and Hawassa use open dumpsites for SW management. Bahir Dar recently installed a rehabilitated dumpsite under the support of UN-Habitat and donors. However, as of early 2022 the site is still waiting for equipment necessary for operation. Landfilling remains a cost-effective method for SW disposal in Ethiopia and most urban areas also have aged, poorly managed, or unmanaged open dumpsites.

Summary of municipal SW management in study cities

Table 12 below shows a summary of the general status of disposal and waste facilities in the three Ethiopian cities. In general, in Ethiopia the responsibility for waste disposal falls on the generator and not the producer, which means there is no current extended producer responsibility (EPR) system in place.

Table 12. Summary of SW and SWM of the study cities

	Addis Ababa	**Bahir Dar**	**Hawassa**
Total municipal SW generated (tons/day)	3200	159	442
Percentage collected (%)	70%	81.3%	80.5%
Percentage recycled	4-5%	unreported	19%
No. of legal landfills	1	1	1
No. of rehabilitated or partially rehabilitated landfills	1	1	0
No. of Waste-to-Energy (WtE) facilities	1	0	0
No. of composting or other recycling facilities	0	1	1

5.2 Impacts and implications of SW and SWM

SW generation and disposal cause various impacts on the environment, human health, economy, and society. SWM also has implications for economic development and environmental management. This section briefly reviews the impacts of SW and SWM.

Environmental Impacts

Air pollution and climate change: Significant amounts of gases are emitted throughout the SW disposal process, such as through trash burning by households or other entities or open trash burning at dumpsites. These emissions can directly affect local air quality and contribute to global climate change. Hazardous gases from the burning of trash (especially plastics and other hazardous materials) at households, landfills, or incinerators can pollute air and harm public health. Carbon dioxide (CO_2) is mostly released during the transportation of SW (from collection vehicles) and the machinery used to manage landfills, as well as from the decay of certain waste materials in landfills. Another greenhouse gas (GHG) emitted in large quantities from SW is methane (CH_4), a compound produced from the anaerobic digestion of wet organic matter by microbial organisms found in abundance at landfills. Additional sources of GHG emissions are from the uncontrolled open burning of SW as well as the spontaneous fires that occur within landfills, which also emit harmful ash or particulate matter that contributes to air pollution. The SW sector normally contributes 3-5% of total GHG emissions in a city. Addis Ababa's anticipated annual GHG emissions are expected to be about 1.5 million tons of CO_2-equivalent by 2030. The WtE facility helps to reduce the overall GHG emissions from the waste disposal process. But inappropriate operation of the WtE facility — for example, the furnace running at a temperature below the required level — can lead to the emission of air pollutants that can form toxic dioxins and other hazardous gases.

Water and land pollution: Open dumping practiced in all three cities is a sizeable contributor to environmental pollution at the local level and downstream in the watershed. SW can be transported from dumpsites by water or wind and pollute nearby ecosystems, vastly expanding the environmental footprint of the site. Poorly managed landfills have proven to create considerable environmental and health risks to the nearby communities of all three Ethiopian cities. These overflowing and poorly designed landfill sites allow the discharge of untreated and contaminated leachate from the stored waste into nearby water systems. Even small amounts of SW leachate can contaminate large volumes of groundwater, which can have widespread impacts on biodiversity and food chains (Oyoo et al., 2014; Nsubuga et al., 2004). Additionally, non-degradable waste (such as plastic) can create blockages in streams and reduce flow rates, causing areas of water to become stagnant and create favorable conditions for breeding pathogens (Kinobe et al., 2015). In Hawassa, the landfill site is less than 500 meters away from a significant waterway, posing enormous environmental and health concerns as the landfill continues to expand beyond capacity. At the Bahir Dar landfill, waste visibly flows uninterrupted into nearby streams.

Health and safety impacts

Infectious disease: All three cities have residents living in very close proximity to landfills. These dwellings subject residents to heightened pathogen exposure, as they facilitate the incubation and proliferation of disease-transporting flies, mosquitoes, and rodents. This increased exposure produces gastrointestinal, dermatological, respiratory, and other kinds of infectious diseases. Dangerous bacteria and other pathogens thrive in landfills due to the large quantities of degrading organic material. The issue with these landfills is that they are "open," meaning pathogens can be carried by winds or rainwater out of the landfill sites and into areas of high human population. Additionally, many people interact closely with the landfill on a daily basis when they walk across it scavenging for valuable materials, increasing their risk of contracting diseases.

Landslides and explosions: The open dumping method these three landfill sites use creates improperly mixed hills of SW. At the Reppie site in Addis Ababa, the waste is spread, leveled, and compacted by bulldozers, and the waste heaps are more than 30 meters tall in some places. Not only is there a continuous risk of injury to the site operators and informal waste pickers that work on this unstable terrain, but there is also the added risk of sudden collapse or even methane gas explosions. In March 2017 in Addis Ababa, a large-scale waste landslide occurred with explosions, resulting in 116 deaths, per official records. Even with best practices, as these sites reach full capacity, the risk of landslides becomes almost unavoidable.

Hazardous waste: There are no established collection systems for household hazardous waste in Addis Ababa, leaving streets as the final collection area for many dangerous materials such as battery waste, biohazardous waste, harsh chemicals, metals, and glass. For larger businesses, institutions, industries, and hospitals, regulations are in place that make them responsible for proper separation and disposal of their hazardous waste. However, due to lack of government enforcement, it is difficult to draw conclusions on the hazardous waste management practices of these large generators. Some informal separation of hazardous waste occurs, but only for profitable recyclable materials such as electrical components and electronic equipment.

Social and economic impacts

Being in proximity to populated areas, these landfills also affect the livelihood of the residents and workers nearby. Foul odors arise from the decaying waste in the landfills and can affect the quality of life of the nearby residents. In Addis Ababa, the facility is adjacent to a community, home to 80,000 of the city's poorest residents who settled there two to three decades ago. Cities in Ethiopia with poorly managed municipal waste have increased health-related risks, especially in neighborhoods with landfills. The residents of the urban slums in proximity to these sites are particularly vulnerable to and acutely affected by poorly disposed waste. Many people in this community reportedly use the dump to sustain their livelihoods (Tassie et al., 2019; Beyene & Banerjee, 2011). The state of a landfill can have other socio-economic impacts, as well. For instance, in Hawassa, as the landfill's area spreads towards residential areas, a general decrease in socio-economic value in the area is being observed. See Chapter 6 for an estimate of the economic impact of landfills on adjacent communities in the study cities.

5.3 Gaps and needs for improvement

Solid waste management is an important aspect of pollution control, as poorly managed waste becomes a potential vector for pollution of water bodies (e.g., through leaching or improper disposal) and ambient air (e.g., through waste burning). Action to improve waste management, such as through better provision of services like source separation and recycling, is therefore necessary not only for control of solid waste, but also as a broader part of an integrated effort to combat all forms of pollution. In order to achieve this goal, a number of gaps and needs must be addressed.

Political will, leadership, and commitments

Though national and municipal strategies and policies are being put in place for initiatives that encourage stakeholders to improve SWM, high municipal government turnover in cities like Addis Ababa make long-term SWM goals difficult to achieve. With short terms for mayors and mid-level municipal positions seeing frequent changes, the environment for completion of SWM measures is challenging. The introduction, implementation, and operation of long-term SWM strategies requires stable and committed leadership at both the municipal and national levels.

Public awareness, private sector engagement, and participation in SWM

SWM spans a vast diversity of sectors and stakeholders, and its success hinges on the continuous participation of residents, businesses, and institutions. Public awareness and participation are particularly important for waste reduction, source separation, and recycling activities. Despite public awareness campaigns, public participation in waste separation and recycling remains low in Addis Ababa. Low public participation leads to low recycling rates, frequent littering, illegal dumping, and uncontrolled burns throughout the city. Successful SWM requires behavioral shifts in order to increase public participation in waste reduction, separation, and recycling. This is often achieved by investing in public education and awareness-raising campaigns, which have proven to be effective in other countries, with success arising from campaigns that include children in schools. In addition to education, well-coordinated SWM plans, and infrastructure investments are needed to improve the accessibility of systems, enable integrated SWM, and allow private markets to capture the value of recycled materials. See Chapter 7 for additional details.

It is commonly thought that the private sector can help with capital financing, cutting the costs of services, managing, and recovering value from waste streams and even moving towards prevention through integrated services. Yet public-private participation or 'privatization' is not necessarily a universal answer for all circumstances, and even when it is appropriate, it needs to be carefully managed. Local authorities have no easy task in selecting the appropriate financing and operator models to ensure the effective delivery of all the various services that make up a municipal SWM system.

Institutional arrangements and capacity

The enacting of SWM policies does not seem to be an issue in Ethiopia and its municipalities, as many regulations are already in place. However, implementing and enforcing policies remains challenging. One issue, for example, is that SWM policies often come without specific targets in terms of collection rates and investment plans. Furthermore, government agencies lack capacity to monitor and enforce existing SWM regulations and standards. According to city officials in Addis Ababa, this seems to be the case for the AAEPGDC, the agency responsible for preparing city environmental regulations, standards, and targets, as well as managing their monitoring and enforcement. Though additional funding is required for monitoring and enforcement measures, improvements in the coordination of existing resources and administrative powers and functions are crucial and require capacity-building support.

Data collection and monitoring

As mentioned above, primary data collection and monitoring are essential to understand the current SWM situation in Ethiopia and to better understand where intervention will deliver the most benefit. Currently there is no established information management system for SWM data in Addis Ababa or Bahir Dar, and only limited SW information is collected in Hawassa. The lack of data on waste that does not reach the WtE or landfill facilities restricts the ability to accurately understand the total volume of SW being generated, its composition, and the proportion reaching waste facilities compared to the proportion uncollected or illegally disposed. To address these data gaps, SWM stakeholders should create a nationally standardized data collection system that houses the information needed to facilitate inter-city comparison and inform SWM decision making.

Outdated landfills

Despite improvements from the Japanese-funded "Emergency Support to SW Management in Ethiopian Cities" project, which has been implemented at open dumpsites, many issues remain surrounding all three cities' landfill sites. Most notably, increasing population growth and poor compaction practices have contributed to landfills reaching their maximum capacities. As described above, poor site management of these outdated landfills has led to environmental and health concerns for nearby residents as well as downstream communities. In Hawassa, rapid urban growth and sprawl has led the once-distant landfill to now be considered well within the urban boundary. Addis Ababa and Bahir Dar have prolonged the lifespan of their landfills and reduced risks of methane explosions by implementing UN-Habitat's Fukuoka Method to manage waste more safely and efficiently. Nonetheless, new sanitary landfills are required in the near future for Addis Ababa, Bahir Dar, and Hawassa.

WtE facilities, like the one in Addis Ababa, appear to be promising solutions for reducing the volume of SW entering landfills. However, their economic and operational requirements likely outweigh their benefits for smaller cities. Development of a WtE facility requires a significant initial investment as well as skilled staff with specific engineering capacities to properly operate the facility. Moreover, WtE facilities require a relatively constant supply of large volumes of waste to maintain steady conditions for efficient transformation of material into energy. They cannot do so where collection coverage is low and inconsistent or where volumes are inadequate, as is the case in smaller cities. As noted above, uncertainties remain regarding the overall environmental impacts, health risks, and profitability of the Reppie WtE facility in Addis Ababa, making it unclear whether this waste management solution is transferrable to other Ethiopian cities.

Financial constraints

For long-term planning, a detailed analysis is needed of the current and projected costs for operating a SWM system in each city. Addis Ababa's investment needs, budget projections, and timeframes have not yet been developed, due to an absence of detailed financial analysis of the solid waste management system. To overcome financial constraints, the cities may have to consider more innovative approaches, especially in the cases of upgrading SWM systems and constructing new sanitary landfills. In addition to seeking international support, the cities should seriously consider promoting private sector participation and attracting private investments in waste separation, recycling, and disposal.

Chapter 6 Economic Costs of Pollution

As preceding chapters have detailed, air, water, and solid waste pollution each have significant impacts on the economy, environment, and human well-being. This chapter estimates in monetary terms these damages, based on standard valuation techniques. It provides a useful order-of-magnitude approximation of the economic cost of air, water, and solid waste pollution that can be used to assess and compare the costs and benefits across environmental media and help prioritize prospective pollution management programs and interventions.

6.1 Calculating the cost of pollution: A methodological overview

According to a total economic value approach, the value of an environmental amenity is the sum of a variety of different forms of value provided by that amenity or ecosystem (World Bank, 2016). The cost of pollution is therefore the sum of damage to each of those uses. Total economic value comprises direct use values (those obtained through direct consumption or non-consumptive use), indirect use values (benefits that don't require direct use, such as ecosystem services), option values (the value of potential future use), and non-use value (such as the cultural value of an environmental resources or the value of its intrinsic existence).

Methods for calculating the cost of pollution damage can be grouped into a few broad categories: market-based methods, revealed preference methods, and stated preference methods (Mendelsohn and Olmstead, 2009). Examples of methods in each category are described below, and the methods applied in this study are laid out in Table 13.

Table 13. Valuation Methods Used in this Study

Method	Description	Application in this study
Market price method	Use prices in existing markets to reflect value of pollution damage	• Lost fish catch at Lake Tana. • Value of lost recyclable waste.
Hedonic pricing	Use the total value of a good to infer value of component parts without market prices. Often used to value environmental amenities that affect the price of residential properties	• Reduction in property values due to proximity to waste disposal sites.
Value of Statistical Life (VSL)	Local trade-off rate between fatality risk and money (total value)	• Premature mortality due to $PM_{2.5}$ air pollution. • Premature mortality due to inadequate WASH • Cost of illness from wastewater-contaminated vegetables.
Value of Statistical Life Years (VSLY)	Local trade-off rate between fatality risk and money (annual value)	• Morbidity due to $PM_{2.5}$ air pollution • Morbidity due to inadequate WASH
Willingness to pay	Survey or "choice experiment" research that asks respondents what they would pay for hypothetical goods or services	• Value of improved water treatment. • value of improved solid waste collection.

Benefits transfer	When data for a study site is unavailable, transfer of values from research in another geographic setting	• VSL for Ethiopia. • willingness to pay for water quality and solid waste collection improvements. • rate of reduced fish catch due to water pollution. • rate of illness from wastewater-contaminated vegetable consumption.

Market-based methods rely on existing markets to determine the value of a good or service. For instance, the market price approach could be used to determine the value of irrigation water purchased by agricultural users according to the price paid for it. In this study, it is used to assess the cost of pollution damage to fish catch, and the value of waste that could be recycled. Revealed preference methods use real-world behavior and market characteristics to measure the value of resources, even if those resources are not a direct part of markets. Hedonic price methods, for instance, are based on the assumption that a good's value is the total of the values of each of its component parts. In this study, hedonic pricing is used to isolate the impact that proximity to waste disposal sites has on property values. In contrast with revealed preference methods, stated preference methods use survey tools to directly solicit information from individuals about the value they place on environmental amenities or their "willingness to pay" for improvements. Contingent valuation surveys are a frequently used stated preference method. They consist of questions that ask respondents to state what value they place on an amenity, along with socioeconomic questions to assess variables that may influence valuations.

In instances when it is not possible to conduct primary research at a study site, or information is not available, the benefits transfer approach is commonly used. This approach involves applying information from studies in other geographic areas to the site of interest. While useful for estimating values when other methods are not feasible, the value of a given resource or cost of pollution may vary between locations based on economic, environmental, social, or cultural factors.

No known research has attempted to estimate the economy-wide impacts of Ethiopian urban pollution in all forms. This study aims to estimate this cost using the methods described above and in Table 13. It draws on available pollution data and valuation literature, and in cases where data is unavailable, aims to make well-reasoned inferences to fill in gaps. The study focuses on a typical (non-pandemic) year, and all costs are expressed in 2019 US dollars unless otherwise noted.

6.2 Cost of Air Pollution

Globally, air pollution is the leading environmental risk factor for premature death, and pollution can also harm ecosystems, reduce agricultural yields, and pose harms to learning and human cognitive function (Xie et al., 2021). The economic value of premature mortality due to exposure to $PM_{2.5}$ is estimated based on the Value of Statistical Life (VSL). It reflects the society's willingness to pay to reduce the risk of death, or rather, the local trade-off rate between fatality risk and money (Viscusi & Masterman, 2017; Kniesner & Viscusi, 2019). Using the World Bank/IHME (2016) guidelines, the VSL for Ethiopia is estimated at US$43,600 for 2019. Applying this value to the 1,600 premature deaths due to $PM_{2.5}$ obtained in section 3.4, the economic cost of premature mortality reaches US$70 million in Addis Ababa.

In addition, the economic cost of morbidity is based on the VSLY concept. This was estimated at about US$1,800, by dividing the VSL by the discounted number of years remaining in an average-aged person in Ethiopia (Robinson & Hammitt, 2018). Applying this estimate to the number of YLDs due to ambient air pollution, the cost of morbidity reaches about US$8 million (see Xie et al., 2021 for more details). Adding up these estimates, the economic cost of health is estimated at US$78 million, which is equivalent to 1.3 percent of the capital's GDP.

A similar valuation effort was conducted for Bahir Dar and Hawassa. Figure 14 in chapter 3 shows that the health effect of $PM_{2.5}$ in these two cities is lower than that in Addis Ababa, primarily due to exposure to lesser $PM_{2.5}$ pollution. Interestingly, the impact in Bahir Dar is slightly higher than that in Hawassa, due to the different age structure of its population: baseline mortality is usually very high among older populations (over 35), and the city has a much larger share of population in this age group compared to Hawassa. Table 14 summarizes the economic costs of air pollution in the three cities. These are conservative estimates, as they do not capture other health impacts that might result from the exposure to $PM_{2.5}$, such as neurological diseases, influenza, and links with COVID-19 infections.

Table 14. Annual Cost of Air Pollution

Pollution damage	**Valuation method**	**Annual Cost: Addis Ababa***	**Annual Cost: Bahir Dar**	**Annual Cost: Hawassa**
Mortality from $PM_{2.5}$ pollution (respiratory infection, cancer, heart disease, stroke, etc.)	Value of Statistical Life	$70m	$4m	$3m
Morbidity from $PM_{2.5}$ pollution (respiratory infection, cancer, heart disease, stroke, etc.)	Value of Statistical Life Years	$8m	$0.5	$0.4
Total		**$78m**	**$4.5m**	**$3.4m**

Source: Xie et al., 2021 for Addis Ababa, authors for Bahir Dar and Hawassa.

6.3 Cost of Water Pollution

The predominant water bodies in Addis Ababa are the Great and Little Akaki Rivers and the Aba Samuel Reservoir; Bahir Dar is situated alongside the Abbay River / Blue Nile at its exit from Lake Tana; and Hawassa sits adjacent to Lake Hawassa. As Chapter 4 describes, these cities generate substantial pollution of their surrounding aquatic environments and suffer from pollution's impacts on their water resources. Each watershed faces significant organic, nutrient, heavy metal, and microbial pollution, as well as the presence of eutrophication and pollution-tolerant taxa. Biological contamination comes from solid waste dumping, sewage, and open defecation. Heavy metal pollution results from industrial discharge into rivers and surface waters.

The costs of water pollution are difficult to measure exactly; however, several factors surrounding water pollution lead to significant economic impacts and other costs. Pollution increases water treatment costs, and—if not all water is treated— pollution reduces the overall quantities of suitable water available to the population for uses such as drinking water, agricultural irrigation, or industrial usage (Yohannes & Elias, 2017). Reduced quantities of suitable water for industrial usage reduces quality and quantity of output from industry and thereby decreases incomes and economic activity (Guta, 2015). There is evidence that water pollution in the study cities also imposes economic costs such as pollution of irrigation water and fisheries. It can also be assumed that there are also damages to non-use values from water pollution, given the presence of rivers and lakes in the study cities.

In addition, water pollution also leads to economic costs in the form of damage to residents' health. The reduced quantity of suitable drinking water leads to an increase in incidence of waterborne diseases and therefore an increase in disease burden. This increase in disease burden reduces the average productivity of a worker, leading to a decrease in income, and also increases healthcare expenses for the population. As such, there is generally a decrease in income and an increase in costs for the average citizen. In addition, a decrease in the quantity of suitable drinking water also increases the disease burden among domesticated animals, such as livestock, leading to deteriorating health, reduced production of milk, and decreased price when sold (Guta, 2015).

Following Croitoru & Sarraf (2017), common illnesses that result from biological water contamination include diarrhea, malnutrition, and typhoid fever. It is also possible that heavy metal pollution in water bodies leads to organ and nervous system damage if it is consumed by humans either directly (Yohannes & Elias 2017) or through crops irrigated with polluted water. Use of unsuitable water for agricultural irrigation can also increase disease burden, since, as discussed above, heavy metals and microbes in agricultural produce still pose a health risk to the population. This burden will then again lead to lower incomes and higher healthcare costs.

This study measured the cost of water pollution by 1) determining residents' willingness to pay (WTP) for improved water quality that reduces the health, environmental, and economic impacts of pollution, 2) measuring health damages due to wastewater-irrigated produce, and 3) estimating the value of fish catch lost due to pollution.

Cost of illness due to inadequate water supply, sanitation, and hygiene practices in Addis Ababa

Similar to the case of air pollution, the cost of mortality due to inadequate WASH is valued based on the VSL -- estimated at US$43,600 for Ethiopia (Section 6.2). Applying this figure to the number of premature deaths (725), the cost of mortality is about US$32 million. In addition, the cost of morbidity is calculated based on the VSLY (US$1,800 for Ethiopia), and the number of YLDs due to inadequate WASH (6,710). Accordingly, the cost of morbidity is estimated at US$12 million.

Overall, the estimated health impact due to inadequate WASH in Addis Ababa is US$44 million. This is a conservative estimate, as it only covers a limited set of water-borne diseases, and does not include others such as typhoid. Data limitations prevented the valuation of similar health impacts for Hawassa and Bahir Dar.

Willingness to pay for improved water quality

There have been studies (Teshager, 2014; Woldemariam et al., 2016) on willingness to pay for water quality improvements in the urban Ethiopian context (see Box 2). They provide useful analytical results for this study to estimate the value of water pollution.

Box 2: WTP Studies on Water Pollution in Ethiopia

Teshager (2014) conducted a willingness-to-pay study for river water quality improvements with 315 Addis Ababa residents. They found that respondents were willing to pay 90 ETB per year (2014 prices) for a one "level" improvement in water quality (e.g., from "moderate" to "good" or "good" to "very good"). And in data from 2011 collected by Woldemariam et al. (2016), Addis Ababa residents reported via choice experiment a willingness to pay 186 ETB per year for "medium" improvement in liquid waste treatment—defined as a medium quality of treated liquid waste by two sewage treatment plants. Before asking for WTP responses, researchers indicated to participants that improvements in liquid waste treatment could lead to reductions in river water pollution, and consequent environmental, health, recreational, economic, and aesthetic benefits. Respondents further reported a willingness to pay 321 ETB/year for "aggressive" improvement—liquid waste treated to very high-quality standards at four treatment plants.

This study adopts the WTP value of Woldemariam et al. (2016) since the value of treated water more closely captures the use value of water than the quality of water in situ in water bodies. That is, in considering willingness to pay for river water quality, residents may not consider uses such as drinking water, especially given that Addis Ababa's drinking water supply comes largely from groundwater. Further, given that the "aggressive" improvements described in the box above would more effectively eliminate pollution than "medium" improvements, the aggressive improvement scenario is chosen in this study to represent pollution cost.

Before stating their willingness to pay for improvements, participants in the study were read a description of current water quality challenges in Addis Ababa, including river water quality, recreation, smell, environmental impacts, health hazards, restrictions on irrigation, and pollution impediments to tourism. They were then informed how much they would hypothetically be willing to pay for medium or aggressive improvement in these conditions. This study derived a current and city-wide willingness to pay for water quality improvements in Addis Ababa from Woldemariam et al.'s data by undertaking the following steps:

- Convert the willingness-to-pay values from ETB to USD, using the average exchange rate for 2011.
- Adjust the willingness-to-pay values reported by residents in 2011 for inflation using the ratio of 2019 to 2011 World Bank GDP deflator values for the United States.[9]
- Convert the per-household WTP values reported by Woldemariam et al. to per-individual values, based on a national average household size of 4.6, according to the United Nations (2019), then multiply by Addis Ababa's 2019 population of 4.6 million.

The result is a willingness to pay US$21.6 million per year across Addis Ababa for aggressive improvement in water quality. To avoid double counting between willingness-to-pay and cost-of-illness approaches, however, 50% of the willingness-to-pay value was discounted for Addis Ababa. Woldemariam et al. place

[9] Because many of the resources valued in this study are tradeable, this study follows the guidance of Turner et al. (2019), first converting values in ETB to US dollars using the average exchange rate in the year the values were originally calculated. Then, the US dollars are adjusted for inflation using GDP deflator values for the United States.

equal emphasis on health and environmental considerations of water quality in their study design, therefore this study assumed that 50% of response value reflects health impacts of water pollution. Accordingly, the study found that Addis Ababa residents are willing to pay a total of US$10.8 million per year for improvements to the non-health-related aspects of water quality.

A benefit transfer of the non-discounted value was used to estimate the equivalent willingness to pay in Bahir Dar and Hawassa. The same methodology was used, along with one additional step: an income adjustment to WTP, assuming an elasticity of 0.1 (Damigos et al., 2016). This benefit transfer assumes that residents of Bahir Dar and Hawassa, apart from income adjustments, are equally willing to pay for water quality improvements. Apart from the adjustment applied to Bahir Dar, it also assumes that the two cities face a level of pollution similar to Addis Ababa. Applying these methods to the other study cities via benefit transfer results in a cost of US$1.3 million per year in Bahir Dar and US$1.8 million in Hawassa.[10] In Woldemariam et al.'s WTP study, researchers told respondents that improvements in water quality would allow "unrestricted irrigation of crops to be eaten uncooked by consumers." However, the study did not directly mention present health risks from wastewater-irrigated produce. It also does not address the potential for pollution to impact fisheries. Therefore, it is assumed that the WTP values in the section above do not reflect the pollution costs from wastewater irrigation or reduction in fish catch, and it is appropriate to measure their cost separately.

Costs from wastewater irrigated produce

At least 1,240 hectares of farmland around Addis Ababa are irrigated with wastewater from the Little Akaki River (Weldesilassie et al., 2011). 60% of vegetables consumed in Addis Ababa were estimated to be irrigated with wastewater in 2011 (Woldetsadik et al., 2017; Gashaye, 2020). Wastewater irrigation imposes several potential costs, including health risks to producers, health risks to consumers of crops, and damages to farm production, including soil salinization, heavy metal pollution, overfertilization, and loss of yield.

This study valued only health costs to consumers of wastewater-irrigated crops, even though wastewater irrigation also poses potential health risks to farmers. In a survey conducted in 2006, wastewater-irrigating Addis Ababa farmers reported losing 57.8 workdays per year to intestinal illness from wastewater, a figure that the researchers deemed implausibly high (Weldeselassie et al., 2011). Based on costs of medical treatment and lost labor, the study found a marginal health cost of wastewater irrigation of 319.90 ETB per person. Dreschel et al. (2015) note that farmers in India reported a total of 24 to 72 days of lost labor from all illnesses, and also that the medical costs reported by the Addis Ababa survey respondents seemed unrealistic (about US$23 for deworming when treatments generally cost around $1). Due to these data uncertainties, the cost of farmer illness was excluded from this study.

The study also did not consider changes in farm productivity due to wastewater irrigation since, in the absence of site-specific data, it is not clear whether the balance of productivity impacts would be positive or negative. The pollution in wastewater irrigation can damage farm operations as described above, but the nutrient content in polluted water can be a resource for farmers. Indeed, wastewater-irrigated crop yield is often higher than similar freshwater farms (Drechsel et al., 2015). Given this uncertainty, farm effects of water pollution were excluded from the valuation.

[10] The assessment of pollution levels in Chapter 4 suggests that Bahir Dar faces less water pollution than Addis Ababa. Therefore, benefit transfer results were discounted by one-quarter for Bahir Dar. The rate of discount was determined according to the proportion of physiochemical water quality parameters that exceed threshold levels in Bahir Dar versus Addis Ababa. See Appendix A for the full set of physiochemical parameters for each city.

To measure the health damages from consumption of wastewater-irrigated crops, a benefit transfer approach was used due to the lack of local data. Seidu & Drechsel (2010) found that health risks from consumption of wastewater-irrigated lettuce resulted in the loss of 12,000 disability-adjusted life years (DALY) annually due to rotavirus in Ghana's five largest cities.

To transfer this data to the Addis Ababa context, the following steps were conducted:

- Adjust the Ghana values to account for differences in population. Ghana's five largest cities had a total population of around 5 million when the data was collected in 2010, compared to the 4.6 million population of Addis Ababa. Both sites were assumed to have equal DALY-to-population ratios. (Seidu & Drechsel estimate that of Ghana's 5 million urban residents, 700,000 are exposed daily to wastewater-irrigated lettuce.)
- Adjust based on the share of Addis Ababa residents exposed to wastewater-irrigated vegetables. Surveys indicate that 99.8% of Addis Ababa residents consume vegetables (Wolle et al., 2020), and data suggests that 60% of the vegetables consumed in the city are irrigated with wastewater (Woldetsadik et al., 2017). Accordingly, it is assumed that exposure in Addis Ababa is around 60% of that found in Ghana, on a per-capita basis.[11]

These conversions suggest a loss of around 7,000 DALY annually in Addis Ababa from contaminated produce. At a value of statistical life year of US$1,800 (World Bank 2021), damages from wastewater irrigation amount to US$11.9 million. Wastewater irrigation is also present in Bahir Dar and Hawassa, though its extent is unclear. To generate estimates for the secondary cities, the Addis Ababa values were converted according to the population of the two cities, and all other parameters were kept constant (apart from a discount applied due to lesser pollution in Bahir Dar, as described above). Therefore, it is estimated that consumption of contaminated produce results in damage of US$720,000 and US$1 million in Bahir Dar and Hawassa, respectively.

This benefit transfer from literature in Ghana should be considered an order-of-magnitude estimate, since it requires various assumptions, such as: assuming that Ghanaian and Ethiopian consumers eat similar amounts of vegetables, assuming that wastewater is equally polluted at both sites, and assuming that sanitation practices (such as vegetable washing and cooking) are similar at both sites.

Because the Ghana studies considered the risk only from lettuce production and no other vegetables, it can be assumed the benefit transfer represents a lower bound estimate. Furthermore, based on the description of wastewater irrigation sites in Obuobie et al. (2006), it appears that less crop area is wastewater-irrigated in the Ghana sites, also suggesting the proportion of wastewater-irrigated produce is higher in Ethiopian cities and therefore health costs are greater.

Costs of lost fish catch

Ethiopian water bodies have a potential fish catch of 94,500 tonnes per year according to an estimate from FAO in 2012, and actual catch was only 15,389 tons in 2014 (Tesfahun, 2019). Tesfahun lists several factors that keep actual catch below potential: pollution from textiles, floriculture, tannery industries; agriculture; and other economic, social, and ecological factors.

[11] The extent of wastewater irrigation in Ghana is not clear. Therefore, this study assumed that 100% of the lettuce consumed in Ghana is wastewater irrigated. For the purposes of calculating costs in Ethiopia, this is the most conservative assumption, as a lower proportion of wastewater irrigation in Ghana would *increase* the relative exposure of Ethiopian consumers compared to Ghana, which would yield higher costs in Ethiopia via benefit transfer.

In their valuation of water pollution in Tunisia, Croitoru et al. (2010) estimated the value of lost saltwater fish catch by comparing catch in polluted versus unpolluted coastal areas, then assuming 20-30% of the difference could be ascribed to pollution. Since this study compares actual fish catch to potential, rather than actual fish catch between sites, it ascribes a lower estimated share of the differential—10 percent—to pollution impacts.

Bahir Dar lies on the coast of Lake Tana, which has an estimated maximum sustainable yield of 15,000 tonnes of fish catch per year and actual annual catch of 9,980 tonnes (Mengistu et al., 2017). Benefit transfer of Croitoru & Sarraf's methods to Bahir Dar result in about US$500,000 worth of damage to fish catch from pollution each year.

Because Addis Ababa is not a major site of fishing activity, the value of lost catch is assumed to be zero. Hawassa was also assigned a value of zero, since fish catch on Lake Hawassa is already estimated to be at or near maximum sustainable yield (Janko, 2014). It is reasonable to expect, however, that these assumptions are underestimates, since some fishing could conceivably take place on Addis Ababa rivers, and yield could still feasibly be higher on Lake Hawassa absent pollution. Therefore, as with the other calculations, the value ascribed to lost fish catch in this study should be considered a conservative estimate.

Summary of water pollution costs

Table 15 shows the total annual cost of water pollution in 2019 US dollars.

Table 15. Annual Cost of Water Pollution

<table>
<tr><th>Pollution damage</th><th>Valuation method</th><th>Cost: Addis Ababa</th><th>Cost: Bahir Dar</th><th>Cost: Hawassa</th></tr>
<tr><td>Mortality from inadequate WASH</td><td>Value of Statistical Life (Addis Ababa); Woldemariam et al. (2016) study of willingness to pay for improved water treatment (Bahir Dar, Hawassa)</td><td>$32m</td><td rowspan="4">$1.3m</td><td rowspan="4">$1.8m</td></tr>
<tr><td>Morbidity from inadequate WASH</td><td>Value of Statistical Life Years (Addis Ababa); Woldemariam et al. (2016) study of willingness to pay for improved water treatment (Bahir Dar, Hawassa)</td><td>$12m</td></tr>
<tr><td>Environmental degradation from pollution in water bodies</td><td rowspan="2">Willingness to pay for improved water treatment (Woldemariam et al. 2016 study of Addis Ababa – benefit transfer to secondary cities)</td><td rowspan="2">$10.8m</td></tr>
<tr><td>Damage to recreational, intangible value of water resources</td></tr>
</table>

Health risk from consuming produce contaminated by wastewater irrigation	Cost of illness from consuming contaminated vegetables (benefit transfer from Ghana)	$11.8m	$0.7m	$1.0m
Reduction in fish catch due to water pollution	Market value of fish; estimate of reduced catch due to pollution (benefit transfer from Tunisia)	$0	$0.5m	$0
Total		**$66.6m**	**$2.5m**	**$2.8m**

As a validation of these results, we note that Damania et al. (2019) found that, globally, areas with significant water pollution have an average GDP growth one-third lower than unpolluted areas. Based on global average GDP growth, this difference amounted to 0.82 percentage points. We found that the cost of water pollution in Ethiopian cities closely resembles this 0.82% figure (though in the case of Ethiopia, this amounts to significantly less than one-third of GDP growth).

6.4 Cost of Solid Waste Pollution

Addis Ababa, Hawassa, and Bahir Dar face significant solid waste management challenges. Municipal solid waste collection rates in the three cities range from 57 to 85%. In Addis Ababa, waste that is not collected and transported to Reppie WTP facility or disposed in the aging Reppie landfill is either littered or open-burned (Xie & Mito, 2021). Recycling rates are low in all three study cities.

Poor solid waste management can cause various impacts on ecosystems, economies, and human health through soil contamination, water pollution, fires at disposal sites, loss of productivity, loss of useful materials, decreased property value, and infection and disease. This study conducted a valuation of solid waste pollution by estimating residents' willingness to pay for improved waste collection, estimating the value of potentially recyclable material lost due to improper disposal, and estimating the reduction in property value of land adjacent to landfill sites.

Other potential damages—for instance, such as health impacts on formal and informal workers handling solid waste—are not directly valued in this study due to feasibility issues or lack of appropriate data.

Benefits of improved SW collection services: a willingness-to-pay approach

To determine willingness to pay for improved waste collection in the study cities, a benefit transfer of data from a 2012 willingness-to-pay study of Mekelle, Ethiopia was used (Hagos et al. 2012).[12] The study asked 226 households about their awareness of the city's current solid waste situation, and how much they would be willing to pay for a hypothetical set of improvements in waste management service. As converted by Damigos et al. (2016), Mekelle households are willing to pay around US$46 per year in 2014 US dollars

[12] Damigos et al. conducted a meta-regression analysis of waste management willingness-to-pay studies across the world, and found that the mean household WTP in Africa is US$90 per year (in 2014 dollars). However, we chose to conduct a benefit transfer of values from the Mekelle study due to its proximity to our study cities, and also because it would produce a more conservative estimation of willingness-to-pay than the continent-wide values.

for improved waste collection.[13] These values were transferred to the context of the three sites in this study, via the following steps:

- Adjust Mekelle WTP values based on the estimated difference in GDP per capita between cities, assuming an income elasticity of willingness to pay of 0.1 (Damigos et al., 2016).
- Express household WTP on a per-individual basis, assuming household size of 4.6.
- Adjust for inflation using World Bank GDP deflator values for US dollars.

With this approach, it is estimated that households in 2019 were willing to pay around $50 per year in 2019 for solid waste improvements. In total, that means residents of Addis Ababa are willing to pay a total of US$53 million for improvements in solid waste collection. Hawassa and Bahir Dar residents are willing to pay US$4.2 million and US$4.1 million, respectively. These values may be underestimates, however, considering that Mekelle has one of the highest solid waste collection rates among Ethiopian cities (Global Methane Initiative 2011). It is logical to assume that residents of cities with more waste uncollected would be willing to pay more for service improvements.

Opportunity-loss of recyclable materials

A portion of solid waste is made up of recyclable material that has market value. In Addis Ababa, waste arrives unseparated at the city's Reppie landfill, where it is then sorted. However, if waste is inefficiently sorted, some fraction of recyclable material may not be recovered. In addition, if waste is not disposed of properly and doesn't get transported to the disposal site, any recyclable material will be lost unless it is recovered by other means.

Addis Ababa generates around 1,168,000 tons of waste each year and recycles around 52,000 tons, for a recycling rate of about 4% by volume. Recycled waste currently generates around ETB 61 million in revenue, equivalent to 1,172 ETB/tonne (World Bank 2021). To estimate the loss of marketable recyclable material under current waste management practices, we estimated the revenue that would be gained if recycling rates in each city increased to 10%—an increase we judged to be achievable based on Xie and Mito (2021). This method assumes that additional waste in all three cities holds the same value of 1,172 ETB per tonne.[14] It also assumes that the market rate for recyclable material is the same in each city, and that markets are able to absorb an increase in supply at constant prices.

If the recycling rate were increased to 10% in Addis Ababa, about 65,000 more tonnes of waste would be recycled each year, worth around US$1.5 million. Bahir Dar generates around 60,000 tonnes of waste per year and recycles an unknown amount (see Chapter 5 for more information, assumed to be 1% for the purposes of this study). Assuming the same conditions as Addis Ababa, an increase in recycling to 10% would generate US$130,000 in value each year. Since Hawassa's recycling rate is already reported to reach 19%, according to the previous chapter, it is assumed that there is no additional recycling value to gain from improved management.

Land value reduction of poor landfill practices

[13] Hagos et al. assessed willingness to pay via two different methods, dichotomous choice (in which participants are presented with a series of specific values and asked their willingness to pay) and open-ended valuation. This study uses the slightly higher dichotomous choice value, as it is considered a more robust valuation method.

[14] While precise data on the composition of recycled waste is not available, UN-Habitat (2021) indicates that 40-50% of household waste is recyclable, suggesting that a substantial increase in recycling is possible based on waste composition.

Landfill sites, especially those poorly managed open dumpsites, pollute air, surface and ground water, and land and cause environmental and health problems in surrounding areas. Finally, the study tries to estimate the environmental cost of landfill in three study cities.

To value these impacts of landfill management, a hedonic pricing approach was used: property values near waste disposal sites were estimated and compared with estimates of value of similar land further away from the landfills. The difference was assumed to be due to the impacts of the landfill site. The area of landfills—official, unofficial, and informal or illegal—was estimated from satellite images or provided by government officials. Ethiopian government representatives also provided typical residential, commercial, and industrial property values for Bahir Dar. Due to lack of additional data, these values were used for all three study cities, and adjusted in proportion to GDP per capita.

Addis Ababa's Reppie landfill is 25 hectares in size (World Bank 2021), and Bahir Dar has one landfill covering 8 hectares in area. Hawassa has two official dumpsites totaling 24 hectares in area, and 3ha worth of unofficial and illegal sites. Because information on unofficial waste sites was not available for Addis Ababa and Bahir Dar, the valuation for Hawassa may be a more complete representation of costs than for the other two cities. Table 16 details the sites and their surrounding land uses. Unless data is available indicating otherwise, all land uses were assumed to take up equal proportions of area (e.g., equal parts residential and commercial land).

Table 16. Landfill Sites in Study Cities

City	Site	Size	Surrounding land uses
Addis Ababa	Official Reppie Landfill	25 ha	Residential, commercial
Bahir Dar	Official landfill	8 ha	Residential, commercial, agricultural
Hawassa	Official landfills	2 sites totaling 24 ha	Residential (75%), social service, agricultural
	Unofficial landfill	0.6 ha	Residential, social service, commercial
	Illegal dumpsite	2 sites totaling 2.4 ha	Residential, social, commercial

A benefit transfer of values from World Bank research on the cost of landfill pollution in Uganda (World Bank, 2022b) was used to estimate loss of property value. This approach is also similar to that used in Croitoru, Miranda, and Sarraf (2019). The World Bank research in Uganda found that land within 30 meters of a dumpsite lost 15% of its value, and land 30-100 meters away lost 10% of its value. Increasingly minor price losses were estimated up to 2km from the landfill site.[15] For the purposes of calculating this adjacent land area, all dumpsites were assumed to be perfect circles. Because lost property values represent a one-time cost and other aspects of this valuation are annual, it was assumed that annual loss is proportional to a 1-to-10 price-to-rent ratio (World Bank, 2022b).

[15] For Bahir Dar and Hawassa, due to the smaller size of landfills, shorter maximum distances were applied.

Accordingly, the cost of pollution from dumpsite waste management in each of the three cities is estimated in Table 17.

Table 17. Annual Cost of Dumpsite Waste Management Pollution

	Cost (USD)
Addis Ababa	$18.7m
Hawassa	$11.8m
Bahir Dar	$5.5m

Because more known landfills exist in Hawassa than in Bahir Dar, the values for Hawassa are much higher than those for Bahir Dar, even though the cities are comparable in size. This suggests that if data on informal and illegal dumpsites were available for the other two study cities, the estimates could be as much as double the values above. Because all three cities dispose of a similar share of waste, it is reasonable to assume that the Addis Ababa and Bahir Dar values are underestimates.

Table 18 depicts the total cost of solid waste pollution in the three study cities.

Table 18. Cost of Solid Waste Pollution

Pollution damage	**Valuation method**	**Cost: Addis Ababa**	**Cost: Bahir Dar**	**Cost: Hawassa**
Health and environmental damage from inadequate waste collection	Willingness to pay for improved collection (benefit transfer of Hagos et al. 2012 study of Mekelle)	$53m	$4.2m	$4.1m
Lost recyclable material due to inadequate collection	Market value of recycling in Addis Ababa (benefit transfer to Bahir Dar and Hawassa)	$1.5m	$0.1m	$0
Contamination and reduced intrinsic value from inadequate landfill management	Hedonic pricing: difference in property value between land near and far from landfills (benefit transfer from West Africa)	$18.7m	$5.5m	$11.8m
Total		**$73.2m**	**$9.8m**	**$15.9m**

6.5 Results and Conclusions

The total annual costs of air, water, and solid waste pollution vary within 3-6% of GDP in the selected cities. Table 19 summarizes the estimated costs. While the methods used in this study result in lower estimated costs for water pollution than for air or solid waste pollution, there is reason to believe that the costs of water pollution, in particular, are underestimated. The impacts of wastewater on human health, ecosystems, and agriculture are difficult to quantify due to lack of data and relevant studies. But as other chapters of this report note, large portions of the study cities are not connected to sewerage networks, groundwater is frequently contaminated, and even treated water can be contaminated during distribution. The methods used in this study may not capture all of these costs, as the causal link between water quality and public health is less direct than for other pollution media, and no comprehensive valuation measures are available in the literature. Therefore, policymakers should note that the cost of water pollution may be far greater than reported here, and these results should not be interpreted to suggest that water pollution is less costly than other forms of contamination.

Table 19. Summary of Economic Costs (2019)

	Addis Ababa: USD	Addis Ababa: % GDP	Bahir Dar: USD	Bahir Dar: % GDP	Hawassa: USD	Hawassa: % GDP
Air pollution	$78m	1.3%	$4.5m	1.2%	$3.4m	0.8%
Water pollution	$66.6m	1.1%	$2.5m	0.6%	$2.8m	0.7%
Solid waste pollution	$73.2m	1.2%	$9.8m	2.5%	$15.9m	4.0%
Total	**$217.8m**	**3.6%**	**$16.8m**	**4.3%**	**$22.1m**	**5.5%**

Note: values are rounded.

This study on the cost of pollution faces several limitations. As discussed throughout the preceding sections, these values should be considered order-of-magnitude estimates rather than precise calculations. The results of this study are limited both by the availability of data and the imprecise nature of pollution valuation. Furthermore, these results should be considered conservative estimates of the extent of pollution costs, for two reasons: First, conservative assumptions were used when assigning parameters for the calculations. And second, the specific damages valued represent those for which feasible valuation methods were available and shouldn't be considered a comprehensive set of the possible damages from air, water, or solid waste pollution. It is plausible that urban pollution imposes many other costs beyond the ones described here. For instance, it could reasonably be assumed that some urban pollution causes harms that extend beyond the geographic scope of this study. As the water chapter indicates, for instance, water pollution in Bahir Dar may travel downstream via the Abbay river to other communities. These impacts are not considered in these valuations.

This research has used the best available information and judgment to make useful estimates of the degree of pollution damage in Addis Ababa, Bahir Dar, and Hawassa. More precise and intensive valuation efforts may be necessary to determine the cost-effectiveness of any particular pollution control intervention.

However, these results demonstrate that the combined and separate effects of air, water, and solid waste pollution impose significant costs on Ethiopian urban economies. Furthermore, it is likely that the values provided by participants in willingness-to-pay studies are an expression of significant health burdens on the cities' populations. If efforts to control pollution are not intensified in the country, the scale of pollution damage to development progress will likely continue to grow. Already a substantial burden at 3% or more of GDP, experience from other countries demonstrates that losses will increase with business-as-usual development. Environmental degradation in coastal Benin, Côte d'Ivoire, Senegal, and Togo amounts to an estimated 5.3% of GDP (Croitoru et al. 2019). In the middle-income countries of Egypt and Iran, the cost of environmental degradation is estimated at around 5% and 7% of GDP, respectively (Croitoru and Sarraf, 2010). These costs demonstrate the strong potential value and return on investment of efforts to reduce pollution and bend the environmental Kuznets curve in the study cities.

Chapter 7 Prioritization of and Recommendations for Pollution Management

7.1 Summary and Overall Assessment of Environmental Pollution

Findings from this study demonstrate that environmental pollution is already a pressing problem in Ethiopia and is also poised to grow further if action is not taken. Though the immediate contributors to air, water, and solid waste pollution may differ, they are driven by shared underlying economic and demographic factors. An overall assessment of the pollution situation in Addis Ababa, Bahir Dar, and Hawassa follows for each medium.

Air pollution

The World Health Organization's guideline value for $PM_{2.5}$ pollution is 5µg/m^3, a threshold far exceeded in Addis Ababa, Bahir Dar, and Hawassa. For Addis Ababa, the population-weighted ambient average $PM_{2.5}$ concentration was 30-36 µg/m^3 for 2016-2020. Though the situation in secondary cities is less severe, air pollution is still a problem; annual concentrations for 2016-2019 were estimated at 20 µg/m^3 in Bahir Dar, and 22 µg/m^3 in Hawassa, several times above the WHO threshold value. In Addis Ababa, the main sources of air pollution are vehicle exhaust, residential activities, industry, and resuspended dust. In Hawassa, the main contributor to $PM_{2.5}$ pollution is residential activity, while wind dust is the main source in Bahir Dar. If no preventive actions are taken by the government, AQ in urban Ethiopia will deteriorate over the coming years.

Using Global Burden of Disease methods, ambient $PM_{2.5}$ pollution is estimated to cause around 1,600 premature deaths each year in Addis Ababa, 90 in Bahir Dar, and 70 in Hawassa—along with an estimated 4,100 YLDs in Addis Ababa and a proportional estimate in the secondary cities. As these figures represent only the effects of $PM_{2.5}$ pollution, they should be understood as only a fraction of the total impact of air pollution.

The effects of air pollution in Ethiopian cities are less severe than in other sub-Saharan African cities, e.g., 33 premature deaths per 100,000 urban residents each year in Addis Ababa, compared with 73 in Cairo, 46 in Lagos, and 35 in Abidjan (Xie et al., 2021). The trajectory of the environmental Kuznets curve suggests, however, that, absent interventions to control pollution growth, Ethiopian cities may face a similar scale of pollution as they continue to grow and develop.

Water pollution

Ethiopian cities exceed national or international standards on various dimensions of water quality, including biological, chemical, and heavy metal contamination. Industrial sources are a major contributor to water pollution, with 89% of wastewater volume in Addis Ababa, for instance, coming from the leather and footwear, food and beverage, and textile industries. Agricultural runoff, untreated sewage, improperly disposed solid waste, and non-point sources (such as stormwater runoff) are also sources of water pollution. In the study cities, these sources of pollution result in high levels of organic waste and bacteria in surface waters, eutrophication, heavy metal pollution, and ecological deterioration. Evidence also suggests that surface water pollution leads to contamination of groundwater, which is the main source of drinking water in some study cities. Available data does indicate, however, that water bodies around Bahir Dar are less severely polluted than the Addis Ababa and Hawassa watersheds.

Quantitative estimates of the health and other impacts of water pollution are not as readily available as those for air pollution, as the effects of water pollution are more diffuse. It is likely, however, that residents of the study cities face substantial adverse effects from water pollution. Studies in Addis Ababa indicate that around 25% of the population suffered from a solid waste or sanitation-related disease in 2008, and other research suggests a substantial burden of typhoid fever and diarrhea, diseases with probable links to water quality. As noted in Chapter 6, the estimated cost of water pollution is likely to be underestimated in this report due to lack of data and valuation methods; water pollution should not be assumed to have lower costs than pollution of other media.

Solid waste

The study cities face a large solid waste pollution burden. Solid waste in Ethiopian cities is generated largely by households, commercial areas, large industries, and street sweeping. About 70% of solid waste is collected in Addis Ababa, and around 80% in Bahir Dar and Hawassa, indicating that large fractions of solid waste go uncollected in each study city, resulting in significant solid waste pollution. Recycling rates are low in Addis Ababa (4-5%), unreported for Bahir Dar, and more substantial in Hawassa (19%).

In addition to direct solid waste pollution, improper solid waste management can result in air pollution due to open burning of trash or improper operation of the Addis Ababa waste-to-energy facility. Open dumping of waste can also lead to water pollution, as described above, and land contamination. Direct results of solid waste pollution in Ethiopian cities include the proliferation of infectious disease via insects and rodents that congregate at waste sites; exposure to hazardous waste; and aesthetic impacts such as foul odor. Addis Ababa also has a history of safety issues related to landfill management, most notably the 2017 explosion and landslide at the Reppie landfill, which resulted in over 100 fatalities. This picture suggests that there are important improvements to be made in both waste collection and disposal, and substantial room to increase recycling rates.

International trends – as well as the Environmental Kuznets Curve (EKC) – suggest that as economic development continues, air, water, and solid waste pollution will each continue to rise in Ethiopian cities. However, as indicated in the discussion of the EKC in Chapter 2, the country has the ability to shape the trajectory of pollution and bend the curve. The sections that follow outline a path forward for pollution management in the study cities.

7.2 Prioritization of Pollution Management

Because of the many and varied pollution issues Ethiopian cities face, it will be necessary to prioritize them, and develop criteria for prioritization. It is recommended that the framework applies the criteria of efficacy, efficiency, technical feasibility, and implementation complexity. *Efficacy* refers to the potential pollution reduction impact of an intervention and *efficiency* to its economic cost-benefit or cost-effectiveness. After assessing interventions according to the criteria, measures can be classified into short, medium, and long term based on the magnitude and rapidness of their impact. Interventions can also be tailored to prioritize communities and geographic areas where impact is greatest. Wright & Diab (2011), for instance, developed a scoring system that can be used for air pollution interventions based on localized levels of pollution and population vulnerability. Fernandes et al. (2021) provide a framework for prioritizing watersheds for pollution interventions based on contamination risk and intervention complexity. Frameworks based on water pollution source are also available (Pizzol et al., 2021).

Results from the cost of pollution research in Chapter 6 indicates that air pollution costs about 0.8-1.3% of GDP in the study cities, water pollution 0.6-1.1%, and solid waste pollution 1.2-4.0%. These costs total 3.6% of annual GDP in Addis Ababa, 4.3% in Bahir Dar, and 5.5% in Hawassa. Despite the higher percentage for solid waste, it is possible that the study estimated solid waste pollution costs more completely than those for air or water pollution. Therefore, we tend to conclude that all three forms of pollution impose the same order of magnitude of cost and deserve equal attention and priority in pollution management.

Each form of pollution requires a different set of management measures. Solid waste pollution can be addressed with improvement of solid waste collection and disposal. Solid waste separation and recycling also has potential win-win impacts, since it diverts waste from the stream bound for landfill and generates recyclable material that can be sold on the market. The potential for composting of organic waste is another profitable resource that can potentially be generated through improved collection and sorting. Water pollution can be improved by expanding wastewater collection and treatment. The health impact of water pollution can be reduced by improving water supply standards and human hygiene, each of which break the link between people and polluted water sources. Air pollution is the most difficult to address since it involves multiple sectors and numerous stakeholders. Nobody can avoid breathing polluted air once air pollution takes place. Air pollution control is necessary, but it may be more costly and difficult to mobilize all parties to control air pollution emissions from various sources. However, certain measures outlined in Xie et al. (2021), such as improvements in fuel quality, offer a more straightforward path to implementation.

Given the high and multifactorial pollution burden, interventions that have multiple possible benefits should be prioritized. For instance, efforts to improve solid waste management may have positive effects on water pollution if waste is prevented from entering water bodies. Similarly, improved waste collection may prevent improper dumping, but if it also reduces open burning of trash, it may improve air quality as well.

7.3 Recommendations

In accordance with the prioritization guidance outlined above, there are various steps that can be undertaken to begin enhancing pollution control efforts. Recommendations in the area of institutional arrangements are outlined below, along with actions specific to air, water, and solid waste management.

Institutional arrangements

Previous World Bank research (e.g., Xie et al., 2021) on air pollution in Addis Ababa resulted in a variety of recommendations related to governmental organization, legal and policy issues, data and information management, staffing, capacity building, and public awareness. Many are also directly pertinent to broader pollution management efforts, as described in the below outline of priorities for institutional strengthening.

Clear and stable organizational structure
Important first steps for improving organizational structure include *clarifying the roles and responsibilities of governmental agencies* for pollution management as well as strategizing and setting clear targets, timelines, and M&E arrangements. The existing regulatory framework is built without clear arrangements for effective coordination among the various agencies and institutions involved in pollution management. Thus, it is critical to establish and strengthen coordination and collaboration mechanisms at both federal and regional/city governments in consultation with relevant stakeholders.

Frequent restructuring of ministries with changing responsibilities has also been a challenge. For example, the federal environmental agency has been restructured three times in the last six years; it was reestablished as the Ministry of Environment, Forest and Climate Change (MEFCC) in 2015, changed to a commission accountable to the office of the Prime Minster in 2018, and in 2021 it was reorganized as the Environmental Protection Authority under the Ministry of Planning and Development. The latest reorganization of EPA to entirely focus on regulatory functions appears promising, but it must be supported with commensurate capacity in staffing and resources to be effective in its pollution control mandate.

Staffing and capacity building
Weak technical capacity in the regulatory and management functions of pollution control at all levels has contributed to ineffective direction and implementation of pollution management interventions. For instance, EPA suffers from inadequate budget, lack of skilled human resources, and frequent staff turnover, which exacerbate the challenge. *Sufficient budget and continuous professional development programs* can be developed for the technical staff of relevant government institutions in addition to capacity building for other stakeholders (including the private sector and nongovernment organizations).

Information and knowledge management
Information and knowledge management both within the EPA and with other stakeholders is poor, and most departments operate in "compartmentalized" units without proper sharing of information. Both federal and regional/city level institutions lack comprehensive monitoring, evaluation, and knowledge management systems related to pollution management. Lack of information is a constraint for pollution management because data in most cases are not current and reliable. It is important for regulatory agencies to therefore prioritize the *systematic collection of air, water, and solid waste pollution data*; develop standardized systems for monitoring and reporting; and make data open to the public via the internet. Such information systems can also serve as the foundation for effective public participation in pollution management and environmental decision-making, a right grounded in Ethiopia's 1995 Constitution.

Air pollution

The Ethiopian government has begun to take various actions, including shifting from the use of fossil fuels to renewable energy in the transport and other sectors, to address air pollution issues. The government is also striving to reduce households' dependence on biomass-based fuel (firewood and charcoal) by promoting the use of cleaner cooking technologies as per the goals of the GTP-2 and the CRGE Strategy.

Based on a recent study on AQM by the World Bank (Xie et al., 2021) and this study, selected high priority recommendations to further control air pollution include:

Regulations, policies, and plans
The roles of key government agencies at the federal and municipal level for air quality management should be defined and clarified through a *functional review of relevant agencies*. Policy measures to address air pollution should include *taxation and pricing policies* or other fiscally neutral instruments to encourage leaner vehicles such as hybrids and electric vehicles; upgrading air quality standards, including ambient $PM_{2.5}$ standards; introducing low sulfur fuel standards (starting with 50 ppm and progressing to 10 ppm) and other transport standards; and developing a national urban air quality management strategy and action plan.

Budgeting and capacity building
Improved air quality management will depend on capacity building along the lines outlined in the institutional arrangement recommendations above. The country should *strengthen institutional capacity* of responsible agencies for air quality management, particularly for regulating and enforcing air quality regulations and standards; develop mechanisms for promoting inter-agency and cross-sectoral coordination; and increase government revenue and budgets for air quality management by reviewing/revising environmental taxation and fee systems.

Monitoring and analysis
Improved data on air pollution is critical to more effective control. Ethiopia should develop *standardized systems for monitoring and reporting* ambient air quality and emission levels at critically polluted source

regions in Addis Ababa and other cities and provide open access to air quality data via the internet and mobile apps. The country can also update the results of the emissions inventory and source apportionment studies in the three cities, identify possible interventions, and conduct economic analysis (e.g., cost-effectiveness or cost-benefit analysis) of these alternatives, with the aim of reducing ambient air pollution to specific targets, such as those identified by the annual ambient air quality guidelines of Ethiopia (15 $\mu g/m^3$) and of the WHO (5 $\mu g/m^3$). These interventions can form a roadmap for actions that are most beneficial to improve ambient air quality.

Water pollution

Several measures have the potential to quickly improve water quality in the study cities.

Industrial/commercial point sources

A first area of focus should be industrial/commercial point sources of pollution. The nature of point sources means that often only a small group of actors (such as industrial plants) have to be brought into compliance with effluent treatment requirements. On that front, Ethiopia already has multiple regulations addressing industrial effluents. However, studies (Awoke, et al. 2016) have largely found that these regulations are poorly enforced. As such, the first step should be to *understand why enforcement is poor with the aim of improving enforcement of existing regulations*, which could have a significant impact on pollution. After stepping up enforcement, *regulations should be examined* for how effective they are at preventing the release of pollutants and should then be adjusted appropriately.

Solid and hazardous wastes

A second area of focus should be on solid and hazardous wastes. Ensuring that *landfills and dedicated solid waste disposal sites* are located and constructed so that wastes cannot leach into the water supply would also remove a significant source of pollution. Furthermore, *solid and hazardous waste management* by small businesses (such as car mechanics) and households will be important to reduce urban run-off, which will likely require a mix of regulations and education campaigns.

Remaining non-point sources

In addition, the remaining non-point sources should be addressed. These require significant efforts to address because they depend on a large number of actors and are not concentrated in a single area. However, addressing them remains vital to reducing pollution. The biggest impact on non-point sources would likely be *improvements in sanitation*. This would include elimination of open defecation, ensuring that latrines are placed sufficiently far away from wells and groundwater, and improving fecal sludge management. In addition, it will be important to ensure that farms use measures to *prevent agricultural run-off*, which again will likely require a mix of regulations and education, especially since a lot of the measures that prevent agricultural run-off also prevent the loss of topsoil.

Water resource management, monitoring, and enforcement

In addition to addressing the sources of pollution, water resource management, water quality monitoring, investment in high-quality distribution networks, and environmental enforcement should be strengthened. Currently, only three river basins have dedicated water resource management authorities with the remaining nine river basins managed by a patchwork of authorities. As such, creating *dedicated watershed-level management authorities* to ensure adequate resource management, monitoring, and enforcement would further assist in water quality improvements, since the collected data can be used as a basis for further pollution reduction regulations and interventions. In addition, local utilities should focus on improving and maintaining the quality of their distribution systems, such that clean, treated water from the water supplier stays that way during distribution.

Solid waste pollution

Ethiopia has made some progress in solid waste management, particularly in Addis Ababa. For example, the 50 MW waste-to-energy plant in operation from early 2018 reduced the amount of municipal solid waste landfilled at the Reppie/Koshe solid waste dump site. The City of Addis Ababa has recently updated its solid waste management (SWM) situation assessment and prepared a SWM strategy. Hawassa and Bahir Dar have also prepared integrated SWM plans. However, despite these important strides, solid waste management remains a major problem. The areas highlighted below provide a framework for improving provision of solid waste collection and management services.

Infrastructure investments

Improving SWM in these cities will mainly involve infrastructure investments. First, *improvements in waste collection* are desperately needed to achieve any improvement in the overall SWM process. Waste collection services should be made more accessible to SW generators, by determining a suitable collection model for each city (i.e., either door-to-door collection or communal collection). There is a need to add more collection points, build more transfer stations, and upgrade waste truck fleets and other collection equipment.

Alongside improvements in collection, supporting a *pilot program on recycling* is essential—especially in Addis Ababa and Bahir Dar where it is almost non-existent. There is a proposed pilot recycling-at-source system in Hawassa, where in select neighborhoods the private sector will continue to collect and recycle SW, but the city will fund training and tech support to improve collection rates. Results from this pilot could be used to structure similar pilots in Addis Ababa and Bahir Dar.

Other specific physical investments include hazardous waste management, rehabilitation and safe closure of aged landfill areas, safe expansion of the landfills for short- and medium-term use, and the construction of new sanitary landfills. The cities also need to provide the necessary *support to implement the Fukuoka method* for landfill management, such as the necessary machinery, security, and fire prevention services for effective operation.

Technical support, capacity building, and research

The cities should also provide adequate technical expertise and training to the staff and operators of transfer and sorting stations to reduce the occurrence of improper waste disposal as well as improve the areas' overall cleanliness and safety.

Data and research

To ensure successful interventions, it is crucial to improve SWM data collection and management systems. This means establishing monitoring systems and creating standardized information systems that are consistent across cities. Improved data collection will allow for solid research and feasibility studies to be conducted to help build effective SWM programming and implementation. In Addis Ababa, these studies should include hotspot analyses and a time-motion study for improving the efficiency of waste collection and transportation; market analysis on MSW separation and recycling; study of private sector participation and public-private partnerships (PPP) in SWM; a hazardous waste management study; feasibility study for e-waste recycling and biogas facilities; the planning, feasibility study, and design of a new sanitary landfill; and evaluation of existing WtE operations. This synthesis of SWM-related information will position the city to make informed investments and address issues effectively, with the possibility of being used as a model for other Ethiopian cities.

Waste-to-energy facility
The Reppie waste-to-energy (WtE) facility has the potential to be an important asset for improving solid waste management in Addis Ababa in the future and may be worthy of scaling to other cities in Ethiopia and beyond. However, due to the lack of data, the facility's environmental, economic, and financial performance is unclear. A *performance analysis* on the facility is recommended to improve understanding and help governments in decision-making on future investments.

Public awareness and participation
Public participation takes on particular importance in the management of solid waste. In particular, household participation in waste separation at the source is vital for enhancing recycling and composting practices. Cities must do more on *public education and awareness-raising* to reduce waste generation and increase understanding of the benefits of recycling and composting. Moreover, together with the public and private sectors, the government can first pilot and then scale up *waste separation* at source. Additionally, the cities could provide incentives to motivate communities or districts to keep their streets clean by organizing regular competitions among them and offering awards to the cleanest communities' winners.

Cost-recovery
Collecting SWM fees to reach a full cost recovery has been a great challenge to most cities in the developing world due to residents' low capacity to pay, and the poor financial situation of municipal governments. As discussed earlier, the Government of Addis Ababa has experimented with a number of different approaches for collecting SWM fees from households and entities over the years. Right now, it collects a SWM fee by proportion through water bills. As households' water consumption and SW generation are both linked to their income and economic activities and are likely to correlate with each other, this approach is likely an effective proxy measure for waste generation. Households without connection to municipal water supply are served by solid waste collection associations. For a city lacking means for clearly defining SWM fees by volume and easily collecting them, collecting SWM fees through water bills may be an easy and suitable way for the governments to recover costs. Bahir Dar reportedly has adopted the water-bill-based approach, but Hawassa has not. To streamline fee collection, Hawassa and other Ethiopian cities may consider adopting a similar water bill-based system for the time being. Each city should also ensure that fees are linked to socioeconomic indicators to ensure affordability.

Social inclusion
Any interventions should be financially affordable and socially inclusive and fair. The planning and development of SWM systems should also *address informal recyclers*, whose livelihoods rely on waste picking and recycling activities that account for their social status; their work should be recognized through formalization.

The above recommendations provide a starting point for efforts to bend the curve of pollution in Ethiopia. This study faced several limitations, however. Access to reliable data limits the extent to which the current pollution picture can be understood, and its costs calculated. The limits on travel further increased challenges of data access. Additional research and planning will be needed to translate recommendations into detailed programs of action. Nevertheless, the guidance outlined here offers a framework for ensuring that continued economic growth in Ethiopia proceeds while limiting adverse impacts on air, water, and solid waste management.

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Appendix A: Water Quality Measurements in Selected Study Areas

Table A-1. Physicochemical measurements throughout Addis Ababa

Site	EC *µS/cm*	TDS *mg/L*	TSS *mg/L*	PO_4-P *mg/L*	NO_3-N *mg/L*	NO_2-N *mg/L*	COD *mg/L*	BOD_5 *mg/L*	DO *mg/L*	Turb. *NTU*	pH	Ref
International Standard	<1500[a]	500[a]		0.20[c]	11.3[e]	0.1[b]	25[c]	5[a]	4.50[a]	1[d]	6.5-9[a]	[a]US EPA [b]Aus/NZ [c]EU [d]WHO [e]FAO
Ethiopia Standard	<1000	400	50	0.025	11.3	0.1		5	4		6-9	(EEPA & UNIDO, 2003)
Little Akaki – Dry Season Mean (Median, Range)	**1174 (1290, 465-1705)**	**581 (636, 225-877)**		**5.1 (5.1, 0.36-14.5)**	0.6 (0.39, 0.03-1.8)	**0.11 (0.08, 0.01-0.35)**	**986 (1046, 311-1697)**	**216 (129, 60.1-582)**	**1.6 (0.88, 0.1-5.8)**		7.2 (7.2, 5.6-7.7)	(Angello, Tränckner & Behailu, 2020)
Kebena Watershed – Wet Season	444.50	255	**101.4**	**0.55 (Tot. P)**	**6.30 (Tot. N)**		**63.00**	**25.28**			**6.23**	(Asnake, Worku & Argaw, 2021)
Kebena Watershed – Dry Season	**1801.19**	**900**	**156**	**8.24 (Tot. P)**	**75.86 (Tot. N)**		**99.73**	**64.63**			7.87	(Asnake, Worku & Argaw, 2021)
Shegole – Dry Season				**45.55**	2.39	**0.90**			**0.18**	**239**	7.76	(Adugna, et al., 2019)
Shegole – Wet Season				**14.77**	1.88	**5.37**			5.43	**376**	8.18	(Adugna, et al., 2019)
Little Akaki – Dry Season				**20.97**	1.31	**2.74**			**3.16**	**35**	7.94	(Adugna, et al., 2019)
Little Akaki – Wet Season				**8.92**	2.05	**10.26**			10.26	**661**	8.27	(Adugna, et al., 2019)
Jemo – Dry Season				**41.46**	1.46	**2.62**			**2.62**	**54**	8.01	(Adugna, et al., 2019)

Jemo – Wet Season				**16.55**	2.36	**11.00**			11.00	**302**	8.47	(Adugna, et al., 2019)
Little Akaki – Dry Season	828			**8**	**189**							(Tegegn, 2012)
Little Akaki – Wet Season	552			**1.3**	**30**							(Tegegn, 2012)
Great Akaki – Dry Season	610			**7**	**8**							(Tegegn, 2012)
Great Akaki – Wet Season	380			**0.8**	**116**							(Tegegn, 2012)

Note: Values in bold are outside of the acceptable range of either the international or Ethiopian standard, whichever is more stringent.

Table A-2. Heavy metal concentrations (in μg/L) for sites throughout Addis Ababa

Site	Cr	Mn	Ni	Cu	Zn	Cd	Pb	Fe	As	Ref
WHO Standard	50.0	400.0	70.0	2000.0	3000.0	3.0	10.0	2000.0	10.0	(WHO, 2017)
Ethiopia Standard	50.0	300.0	100.0	112.0	500.0	5.0	50.0	1000.0	50.0	(EEPA & UNIDO, 2003)
Kera River	7.4	**1690.0**	8.9	39.0	193.0	<1.0	**33.0**	**4290**	<1.0	(Itanna, 2002)
Bulbula River	ND		2.3	12.4	50.4	0.07	**14.1**		1.70	(Itanna, 2002)
Modjo River, dry season	17.2	**450.0**	19.8	7.2	22.4	0.07	3.0	**2900**	4.8	(Masresha, et al., 2011)
Modjo River, wet season	**269.0**	**2358.0**	**185.0**	90.9	419.0	0.4	**44.2**	**162000**	**13.5**	(Masresha, et al., 2011)
Awash River inlet, dry season	5.2	209.0	9.7	5.1	10.6	0.0	1.0	**1000**	3.3	(Masresha, et al., 2011)
Awash River inlet, wet season	**239.0**	**3139.0**	**180.0**	89.5	481.0	0.4	**50.9**	**173000**	**12.2**	(Masresha, et al., 2011)
Awash River					107.6	**32.2**	**6090.7**	340.4		(Degefu, et al., 2013)
Little Akaki River	**75**	**320**		10	90					(Adugna, et al., 2019)

(LAR), dry season										
LAR, wet season	**55**	43		3	50					(Adugna, et al., 2019)
LAR upstream of ASR	**220.0**	**1335.0**	60.0	10.0	260.0	ND	ND	**2615.0**		(Kassegne, et al., 2019)
LAR near Gefersa Reservoir	**70.0**	20.0	50.0	ND	210.0	ND	ND	270.0		(Kassegne, et al., 2019)
LAR at Burayu site, AA	2.4	38.0	3.1	5.8	13.0	0.06		974	<1.0	(Aschale, Sileshi & Kelly-Quinn, 2019)
LAR at Kolfea site, AA	**255.0**	**2000.0**	4.9	3.3	21.0	0.06		905	1.3	(Aschale, Sileshi & Kelly-Quinn, 2019)
LAR at Kera site, AA	2.4	**1150.0**	5.2	5.6	21.5	0.06		945	1.1	(Aschale, Sileshi & Kelly-Quinn, 2019)
LAR at Gofa site, AA	3.9	**1300.0**	3.9	6.6	10.9	0.04		565	1.2	(Aschale, Sileshi & Kelly-Quinn, 2019)
LAR at Akaki site, AA	46.0	**1400.0**	6.5	6.4	22.5	0.06		555	1.9	(Aschale, Sileshi & Kelly-Quinn, 2019)
Big Akaki River	**60.0**	**1330.0**	45.0	10.0	245.0	ND	ND	**1335.0**		(Kassegne, et al., 2019)
Akaki River – below ASR	**80.0**	**1760.0**	**70.0**	ND	250.0	ND	ND	600.0		(Kassegne, et al., 2019)
Shegole River, dry season	21	**370**		70	320					(Adugna, et al., 2019)
Shegole River, wet season	10	40		60	110					(Adugna, et al., 2019)

Jemo River, dry season	**63**	**590**		20	100					(Adugna, et al., 2019)
Jemo River, wet season	**60**	58		10	70					(Adugna, et al., 2019)
Kebena River – near Entoto	**90.0**	30.0	**110.0**	ND	310.0	ND	ND	290.0		(Kassegne, et al., 2019)
Aba Samuel Reservoir (ASR)	**77.5**	**1127.5**	52.5	10.0	187.5	ND	**70.0**	**1767.5**		(Kassegne, et al., 2019)
Koka Reservoir, dry season	27.8	**303.0**	22.4	15.5	48.0	0.04	4.9	**6800**	2.8	(Masresha, et al., 2011)
Koka Reservoir, wet season	**50.9**	**422.0**	39.4	20.8	98.4	0.06	8.5	**37000**	2.9	(Masresha, et al., 2011)

Note: This table was adapted from (Getachew, et al., 2021). Values in bold are outside of the acceptable range established by the WHO or the EEPA.

Table A-3. Physicochemical measurements throughout the Lake Hawassa watershed

Site	EC *µS/cm*	TDS *mg/L*	TP *mg/L*	NO_3 *mg/L*	NO_2 *mg/L*	NH_4-N *mg/L*	COD *mg/L*	BOD_5 *mg/L*	DO *mg/L*	Turb *NTU*	pH	Ref
International Standard	<1500[a]	500[a]		50.0[e]	0.1[b]		25[c]	5[a]	4.50[a]	1[d]	6.5-9[a]	[a]US EPA [b]Aus/NZ [c]EU [d]WHO [e]FAO
Ethiopia Standard	<1000	400	0.025	50	0.1	0.2		5	4		6-9	(EEPA & UNIDO, 2003)
Watershed Rivers	235	118		2.7	0.06	**1.2**	**113**	**18**	5.0	**21.5**	7.8	(Lencha, Tränckner & Dananto, 2021)
Lake Point Sources	**3156**	**1525**		7.5	0.07	**7.1**	**368**	**107**	**2.2**	**15.1**	8.3	(Lencha, Tränckner & Dananto, 2021)

Lake Hawassa	853	**437**	**0.32**	7.2	0.04	**2.3**	**129**	**24**	**4.2**	**10.7**	8.6	(Lencha, Tränckner & Dananto, 2021)
Industrial Effluent	**2405**					**6.04**	**435**	**290**	**2.1**		8.7	(Mereta, et al., 2020)
Watershed River Upstream	652					**0.35**	**107**	**71**	**4.1**		7.6	(Mereta, et al., 2020)
Watershed River Downstream	**1157**					**1.6**	**329**	**220**	**2.6**		7.8	(Mereta, et al., 2020)
Lakeshore	**1015**					**1.62**	**177**	**118**	**3.7**		8.7	(Mereta, et al., 2020)
Lake Hawassa dry season	837	**407**		6.2			**200**	**61**	5.2	**6.5**	8.8	(Menberu, Mogesse & Reddythota, 2021)
Lake Hawassa wet season	806	**435**		5.8			**149**	**51**	5.6	**6.1**	**9.1**	(Menberu, Mogesse & Reddythota, 2021)
Tikur Wuha River	**1030**	**518**	**1.3**	3.1				**168**	4.8	**26.6**	6.8	(Haile & Mohammed, 2019)
Lake Hawassa	**1610**	**808**	**1.2**	4.3				**128**	7.7	**41.8**	8.3	(Haile & Mohammed, 2019)
Lake Hawassa – inlet of Tikur Wuha River	701	**421**	**0.449**	3.0	**0.103**		**39**	**95**	11.2	**21**	7.0	(Worako, 2015)
Lake Hawassa	756	**453**	**0.365**	5.5	0.03		**50**	**120**	18.6	**7.0**	7.6	(Worako, 2015)

Note: Values in bold are outside of the acceptable range of either the international or Ethiopian standard, whichever is more stringent.

Table A-4. Heavy metal concentrations (in µg/L) for sites throughout the Lake Hawassa watershed

Site	**Cr**	**Mn**	**Ni**	**Cu**	**Zn**	**Cd**	**Pb**	**Fe**	**As**	**Ref**

WHO Standard	50.0	400.0	70.0	2000.0	3000.0	3.0	10.0	2000.0	10.0	(WHO, 2017)
Ethiopia Standard	50.0	300.0	100.0	112.0	500.0	5.0	50.0	1000.0	50.0	(EEPA & UNIDO, 2003)
Tikur Wuha River	**300**	**1500**		70	**1100**			580		(Haile & Mohammed, 2019)
Lake Hawassa	**363**	**381**		25	**2767**			432		(Haile & Mohammed, 2019)
Lake Hawassa – inlet of Tikur Wuha River	ND	**489**	ND	46	317	ND	ND	180		(Worako, 2015)
Lake Hawassa	ND	44	ND	6.3	181	ND	ND	75		(Worako, 2015)
Lake Hawassa	1.7					0.41	1.0		1.8	(Dsikowitzky, et al., 2013)
Lake Hawassa – near Tikur Wuha inlet	6.48				0.219	0.094	6.1			(Amare, Yimer & Workagegn 2014)
Lake Hawassa – Asama Ber	ND				ND	ND	**49.47**			(Amare, Yimer & Workagegn, 2014)

Note: Values in bold are outside of the acceptable range established by the WHO or the EEPA.

Table A-5. Physicochemical measurements throughout the Lake Tana watershed

Site	**EC** ***µS/cm***	**TDS** ***mg/L***	**TP** ***mg/L***	**NO_3-N** ***mg/L***	**NO_2-N** ***mg/L***	**NH_4-N** ***mg/L***	**COD** ***mg/L***	**BOD_5** ***mg/L***	**DO** ***mg/L***	**Turb** ***NTU***	**pH**	**Ref**
International Standard	<1500[a]	500[a]		11.3[e]	0.1[b]		25[c]	5[a]	4.50[a]	1[d]	6.5-9[a]	[a]US EPA [b]Aus/NZ [c]EU [d]WHO [e]FAO

Ethiopia Standard	<1000	400	0.025	11.3	0.1	0.2		5	4		6-9	(EEPA & UNIDO, 2003)
Lake Tana	143	94	**0.99**	0.79					5.99		7.6	(Kassa & Tibebe, 2019)
Lake Tana Littoral Non-Bahir Dar	125	70	**0.36**	0.13	0.04	0.19				**81**	8.2	(Wondim, 2016)
Lake Tana Littoral Bahir Dar	123	66	**0.23**	0.12	0.02	**0.2**				**28**	8.0	(Wondim, 2016)
Lake Tana Pelagic	133	72	**0.22**	0.09	0.01	0.04				**38**	8.3	(Wondim, 2016)
Lake Tana River Mouth	143	78	**3.1**	0.50	**0.31**	**0.8**				**214**	8.2	(Wondim, 2016)
Tributary Rivers	275	147	**2.3**	0.43	**0.38**	**0.82**				**207**	8.1	(Wondim, 2016)
Lake Tana	335	169									6.5	(Kindie, et al., 2020)
Bahir Dar Urban Runoff	339	178	**0.46**	**23 (TN)**			3.3		**2.8**		6.7	(Wondie, 2009)
Abbay River	12-284	0-180	**0.08-20.6**	0.027-9	**0.0-0.9**	**0.04-6.60**			**1.1-5.1**	**5-1002**	6.6-8.8	(Goshu, Koelmans & de Klein, 2017)
Gumara River	10-280	5-180	**0.03-12**	0.0-1.45	**0.0-11**	**0.02-3.3**			**3.1-7.9**	**8.5-993**	7.4-8.8	(Goshu, Koelmans & de Klein, 2017)
Rib River	11-490	6-240	**0.06-9.7**	0.08-1.55	**0.0-11**	**0.02-1.40**			**3.3-8.6**	**3.1-869**	7.1-8.9	(Goshu, Koelmans & de Klein, 2017)
Dirma River	**100-1000**	**40-490**	**0.04-13.8**	0.15-2.42	**0.01-1.01**	**0.03-5.5**			**2.2-7.2**	**3.0-1002**	**6.4-8.7**	(Goshu, Koelmans & de Klein, 2017)
Megech River	110-380	50-190	**0.07-9.4**	0.01-1.4	**0.02-1.0**	**0.10-2.7**			**3.7-5.9**	**3.9-962**	7.2-8.9	(Goshu, Koelmans & de Klein, 2017)
Arno River	76-271	49-198	**0.36-3.2**	0.25-2.8	0.0-0.01	**0.09-1.3**			**3.0-4.0**	**2.5-1002**	7.9-8.9	(Goshu, Koelmans & de Klein, 2017)

Garno River	180-633	**100-411**	**0.36-2.4**	0.09-2.1	0.0-0.02	**0.02-0.5**			**3.0-4.1**	**2.1-1002**	7.8 - 8.5	(Goshu, Koelmans & de Klein, 2017)
Lake Tana	**100-1000**	148-178	**1**	0-3.66	**0-0.366**	**0-12**		**8.5-226.3**	**3-7.6**	**11.2-125**	6.8 - 8.3	(Goshu, Koelmans & de Klein, 2017)
Lake Tana	171	103	**0.14**	6.18	0.07	**0.24**				**18.7**	7.4	(Ewnetu, Bitew & Chercos, 2014)
Abbay River – upstream of factory	141	102						**5.3**	7.8		7.3	(Mehari, Gebremedhin & Ayele, 2015)
Abbay River – downstream of factory	168	129						**8.2**	7.2		7.7	(Mehari, Gebremedhin & Ayele, 2015)
Abbay River at factory	944	**448**						**33**	6.7		7.1	(Mehari, Gebremedhin & Ayele, 2015)
Textile factory effluent	**1050**	**612**						**40**	**3.7**		8.4	(Mehari, Gebremedhin & Ayele, 2015)
Factory neutr. pond	836	391						**36**	7.7		7.8	(Mehari, Gebremedhin & Ayele, 2015)

Note: Values in bold are outside of the acceptable range of either the international or Ethiopian standard, whichever is more stringent.

Table A-6. Heavy metal concentrations (in µg/L) for sites throughout the Lake Tana watershed

Site	Cr	Mn	Ni	Cu	Zn	Cd	Pb	Fe	As	Ref
WHO Standard	50.0	400.0	70.0	2000.0	3000.0	3.0	10.0	2000.0	10.0	(WHO, 2017)
Ethiopia Standard	50.0	300.0	100.0	112.0	500.0	5.0	50.0	1000.0	50.0	(EEPA & UNIDO, 2003)
Lake Tana – dry season	**103**	**301**		**1368**	**772**	**61**	**955**			(Kassa & Tibebe, 2019)
Lake Tana – wet season	**415**	266		**196**	395	**18**	**300**			(Kassa & Tibebe, 2019)
Lake Tana	11				11.7	ND	ND	375	ND	(Kindie, et al., 2020)

Lake Tana	0.011-0.018					0.002-0.02	0.0-0.043	**2200**		(Goshu, Koelmans & de Klein, 2017)

Note: Values in bold are outside of the acceptable range established by the WHO or the EEPA.

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