Ethiopia Institute of Architecture Building Construction and City Development

# Investigating the Optimum Building Density and Lake Tana’s Breeze in the Case of Bahir Dar city, Ethiopia

By

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A Thesis Submitted to the graduate studies of Addis Ababa University for the partial fulfillment of masters of Science in Urban Design and Development

Addis Ababa University

Addis Ababa, Ethiopia

May, 2021

Addis Ababa University

School of Graduate Study

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# Abstract

*The ideal built-up density for proper ventilation of Bahir Dar city is proposed using a method of performing city-scale ventilation assessment based on remote sensing, GIS, and CFD technology. The ventilation of a city depends on the location and background ventilation source. Bahir Dar is a city found south side of Lake Tana and beginning of River Abay. The ventilation background is assessed using meteorological data of wind direction and speed. The numerical simulation of ventilation potential index performance have done using roughness length (RL), sky view factor (SVF) and computational fluid dynamics (CFD). In this study, the roughness length (RL) determined the land use land cover of land sat 8 and the building morphology of existing development. The sky view factor (SVF) is estimated and calculated by using 30m high resolution digital elevation model by SAGA GIS. The general wind pattern and ventilation of the existing high rise building is evaluated by CFD simulation. Generally, the existing ventilation performance of Bahir Dar is relatively high. But in the southern part of the city ventilation is moderate (general) and low. The new structure plan of Bahir Dar city have been checked by the above criteria and the result shows high roughness length and low ventilation performance because of high density development proposal and block Lake Tana breez's. Suitability map developed by using multiple criteria; exiting ventilation potential, major ventilation source, urban ventilation corridor buffering standard and sky view factor have been used to produce suitability map of urban ventilation corridor design. The ventilation corridor design result perform a ventilation potential index value 0.4 with low roughness value of 0.5 and high sky view factor 0.67. Accordingly, the municipality of Bahir Dar should adopt an optimal citywide development density of not more than 50%, a minimum of 15m distance between buildings, and a maximum building size (footprint) of 20m x30m.*

**Key Words**: - Ventilation potential index, Suitability map, ventilation corridor, & sky view factor

# Acknowledgment

First of all, I would like to thank the Almighty of God who helped and guided me in all aspects of my life especially to accomplish this work. Glory to his Almighty for his care and smoothening challenges in doing this paper. I would like to express my gratitude to my advisor Dr. Tibebu Assefa for his diligent support, guidance, and encouragement right from the beginning of the research up to the realization of this paper. He also gives me new insight and inspiration toward thesis and academics relating to the current urban challenges.

I am particularly grateful to the National Meteorology Agency professionals for providing me climate data and information. I would also like to thanks my friends, instructors, and classmate who encouraged me in my paper accomplishment. Last but not least, I would like to thank my family for their encouragement all along with my study.

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# Acronyms

| | |
|---|---|
| **BAR** | Built-up area ratio |
| **BCR** | Building coverage ratio |
| **BH** | Building height |
| **CBD** | Central business district |
| **CFD** | Computational fluid dynamics |
| **DEM** | Digital elevation model |
| **FAR** | Floor area ratio |
| **GIS** | Geographic information system |
| **LCZ** | Local climate zone |
| **NMAE** | National meteorological agency of Ethiopia |
| **RL** | Roughness length |
| **RS** | Remote sensing |
| **SVF** | Sky view factor |
| **UHIL** | Urban heat island |

# CHAPTER ONE

# INTRODUCTION

## 1.1 Background

Nowadays, humans live in a critical environmental situation characterized essentially by global warming. One of the most important indicators of this situation is the effects of heat on urban buildings and streets. Cities are growing at a fast rate with higher density, narrower urban corridors, and more high-rise urban structures. Following this, the deterioration of the urban environment becomes a scorch concern (Wong, 2015). Thus, in urban areas, the temperature is high and generates discomfort in outdoor living spaces.

The urbanization process structurally modifies natural ventilation as attested by several scientific researches that indicate that disorderly urban growth is responsible for changing local climatic parameters, compromising thermal comfort conditions. These issues are linked to urban planning (Stewart and Oke, 2006).

The process of urbanization increases the use of natural land by conversion into built and changing the natural ventilation process and as result decreasing the supply of fresh air for the residence of cities.

Urban form is the result of interactions between buildings' heights, the distance between buildings, and occupancy rate, changing the permeability of the wind within the urban fabric and influencing its use for passive cooling of buildings (Proceedings of Building Simulation, 2011).

Using CFD modeling to analyze the ventilation of cities is developed from time to time but most of the applications are worked in the single building passive heating and cooling system (Duarte & Serra (2003). Cities had to get passive cooling and heating system from the surrounding air. Natural ventilation area affected by the development density, size, orientation of the street system.

As Prata-Shimomura et al, (2009) attest, verifying natural ventilation conditions through models assists the architectural design and urban planning process. Wind tunnel tests, software's or mathematical models are important tools in the analysis of urban transformations, allowing greater precision in the airflow assessment in internal and external environments.

Designing ventilation corridor of Bahir Dar City for natural breeze from Lake Tana fresh air by investigating roughness length (RL), sky view factor (SVF), CFD test of urban morphology of existing city development and design ventilation corridor with high sky view factor and low roughness of city.

Investigating the existing ventilation potential of Bahir Dar by roughness length (RL), sky view factor (SVF) and CFD simulation and design urban ventilation corridor with optimum built environment density of Bahir Dar for maximum ventilation potential index.

## 1.2 Statement of the problem

Natural ventilation is the intentional flow of outdoor air through an enclosure under the influence of wind and thermal pressures through cities and buildings (ASHRAE, 2005). Natural ventilation is a more effective instrument to improve indoor and outdoor air quality in urban areas, to protect health, to provide thermal comfort and to reduce unnecessary energy consumption (Deriba, 2020) .

The environmental problems related to city planning, architecture, and urban design require climate-responsive architecture and city planning. The sustainable city planning and building system need careful consideration of microclimate conditions and characteristics (Bekele *et al.*, 2008).

The complex geometry of built-up areas constituting the roughest of the Earth's surfaces, either natural or man-made, leads to enormous complexities in the patterns of airflow which vary very sharply in both space and time. Accelerations and decelerations, gusts and lulls, eddies, and jet-like flows are to be found closely juxtaposed from one place to another in the city and from one to the next. But the extreme complexities and gradients of wind speed and direction to be found in urban areas are intensifications of conditions that everywhere characterize the atmospheric boundary layer. The roughness of the urban surface merely accentuates universal features of the lower 600 m or so of air (Liu *et al.*, 2016).

Bahir Dar is city cooled by Lake Tana (McCann, 1997). However, the city design and master plan preparation do not consider the wind source of Lake Tana. The current design practices only consider the physical pattern of the city. Because of this, the city’s temperature is increasing due to increasing growth in building density. Therefore, the city needs to look for other mechanisms to keep the city cool and accessible for natural breath.

Even if the lake is found alongside the city that has a capacity to cool the air, the residence are sensing and complaining the increment of temperatures from year to year.

The unexpected increment of temperature and creation of wind shadow in Bahir Dar city needs to be addressed by a passive cooling urban design solution. Among the different options, street orientation and optimum building density design based on CFD wind simulation and Sky view factor (SVF) can be as one of the solution for the city breath source in a passive way from the lake. This study has sought to design the city according to the wind to get a city breath in a passive way using CFD and SVF.

## 1.3 Objectives

**Main objective:**

To determine the optimum building density of a city based on investigating Lake Tana's Breeze.

**Specific objectives:**

1. To identify the wind pattern at the microscale of the city.
2. To find the size and optimum form that conform to the lake breeze.

## 1.4 Research questions

**Main question:**

How to determine the optimum building density of a city by understanding the Lake Tana in Breeze of Bahir Dar city, Ethiopia?

**Specific research questions:**

1. How is the city breeze at the microscale?
2. What type of size and optimum form conforms to the lake breeze?

## 1.5 Scope of study

The study was confined to places having dense high rise building of Bahir Dar city; especially the CBD and tried to simulate all the components that affect and also useful for the best ventilation corridor of the city. The study addressed the issue of existing ventilation potential, determination of optimum building density, and provide optimum building height.

## 1.6 Significance of study

The study will be very important for people to live a comfortable and high quality of life by ensuring natural ventilation air into the city without interruption of the density of development.

It is also used by researchers and design professionals for guiding the applicability of climate-responsive building designs that evaluate the resources of local climate and quantify the passive performance of the building and city in a way that is sensitive and accurate enough to reflect the impact of small design changes.

Finally, the study will bring a rule of thumb for planning authorities to control development, to develop optimum density of a city that decides the passive city breeze condition, and to consider microclimate condition when designing a city and building.

## 1.7 Limitation

The simulation only tests the building model and orientation without other determinants like the tree, building texture, the opening of the building. This is because that the software needs a high quality computer and a large coverage of the study area that influence wind movement.

## 1.8 Organization of the paper

This paper is organized into six chapters. The first chapter is an introduction which includes a statement of the problem, objective of the study, basic research questions, and significance of the study, scope, and limitation of the study. The second chapter deals with literature related to the topic and contextual review. The third chapter deals with the material and methods of the study that includes study area description, method of data collection, and method of data analysis. Chapter four is about the results of the analysis and the research. Chapter five is devoted to discussion. Finally, chapter six is devoted to conclusion and recommendations.

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1 Theoretical Review

Wind is the flow of air across the earth’s surface. Wind is created by differences in atmospheric pressure that force air to flow from higher pressure zones to lower pressure zones (SEDA, 2001). The generation of wind can be attributed to both global and local effects. On a global scale, the wind is created by the pressure difference due to unequal heating of the earth’s surface by the sun or solar energy. Solar radiation covers a large area around the equator than the poles of the earth's surface, and it decreases from the equator to the poles because of high latitudes. (V, Pandey et al., 2019).

### 2.1.1 Wind and Urban

Urban areas should be planned and designed to ensure the living comfort, health, and safety of their inhabitants and users. Although thermal comfort is also important (Blocken et al., 2012), these of the above concepts have high value for city growth, sustainability, and formation of a healthy environment. Throughout history different communities have created a culture and building methodology to adapt to the surrounding environment. In other words, humans has tried to create comfort for living without technology on the passive system (Victor Olgay, 2015). Currently different urban areas are growing dramatically, but the design system has not considered the climate condition and comfort system. The urban area built the same building on a different city and different environment (Victor Olgay, 2015). Because of this, the city needs an active mechanism of cooling and heating system. The micro climate in an urban areas depends on the built environment as well as the location of the urban area. The micro climate of the city in the temperate region is different from the cities located in a hot and humid region. In hot and humid cities design is promoting the ventilation of streets and decreases wind shadow (Bekele *et al.*, 2008). Winds are governed by the dynamics of the atmosphere closest to the surface, the atmospheric boundary layer (Droste et al., 2018). When the vertical built environment is increasing the surface-atmosphere is far from the ground that has increasing ground temperatures. The urban environment is characterized heterogynous landscape and built environment that creates complex micro-climate and ventilation value of the cities (Droste et al., 2018). Environmental changes brought about by urbanization have been studied by researchers in medicine, agriculture, geography, and climatology (Emmanuel and Johansson, 2006). Application of this knowledge in urban planning and related field is very low, but designing the city without microclimate study is difficult because of global climate change and variabilities.

### 2.1.2 Urban morphology and ventilation corridor

It is well known that urbanization has not only gradually changed the land cover and urban form through construction works and urban sprawl, but has also affected urban climatic conditions (Emmanuel and Johansson, 2006). However, communication between urban planners and urban climatologists is limited due to their different working vocabularies (Mills, 2016). Therefor it needs a consideration of the effect of urban morphology on the microclimate when designing a city to decrease its impact on the natural ventilation.

The local climate zone (LCZ) scheme, developed by Stewart and Oke, (2006), represents one recent effort in urban climatic application to link urban morphology and urban climatic conditions. A set of parameters were selected to define a site's LCZ class by its geometric and surface cover parameters; these include sky view factor, aspect ratio, building surface fraction, impervious surface fraction, pervious surface fraction, building height, and terrain roughness (Stewart and Oke,2006). *Figure 1* shows that the variation of ventilation performances from natural earth to high density urban built.

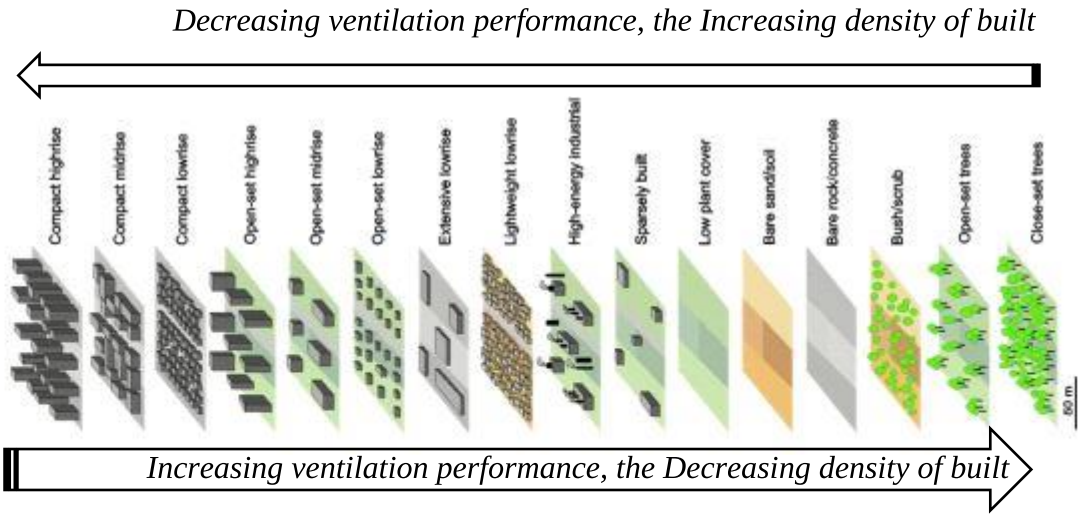


Figure 1: Thermal differentiation of local climate zones (source: Stewart and Oke, 2006)

The concept of urban ventilation corridor, which can also be called wind corridor, in the major fresh air source of specified urban areas (Ren *et al.*, 2018). The ventilation corridor quality depends on the air source and atmospheric environment. The fresh air from lake is the dominant of wind corridor. Table one show the major UHIL classification of daily and monthly temperature values.

Table 1: Classification of UHIL

| Classification | Description | Daily urban UHIL ($^oC$) | Monthly UHIL ($^oC$) |
|---|---|---|---|
| 1 | Strong cool island effect | ≤ -7 | ≤ -5 |
| 2 | Relative cool island effect | (-7.0 , -5.0) | (-5.0, -3.0) |
| 3 | Slightly cool island | (-5.0, -3.0) | (-3.0, - 1.0) |
| 4 | No heat island | (-3.0, 3.0) | (-1.0 , 1.0) |
| 5 | Slightly heat island | (3.0, 5.0) | ( 1.0, 3.0) |
| 6 | Relatively heat island | (5.0, 7.0) | (3.0, 5.0) |
| 7 | Strong heat island effect | >7 | >5 |

(Source: Ren *et al.*, 2018)

Urban ventilation corridor is the use of wind characteristics from the ventilation system, under the effect of wind pressure, the city suburb of fresh air into the city, urban carbon-oxygen balance, adjust the microclimate (Su et al. , 2016). The creation of good ventilation corridor for a city depends on the urban design morphology and orientation of the city. In different cities and climate conditions, different types of urban form are found. The form and volume of an urban blocks have a determinant value to get air or block air for the surrounding area (Guan et al., 2011). The urban ventilation path, scattered morphology, and green space system have remarkable effect on promoting ventilation and alleviating the urban heat island effect; the wall effect formed by high-rise buildings with a large podium is very unfavorable to the ventilation. It is required to strictly control the bulk and appropriately increase the height (Zhu, 2017). Lateral spacing between buildings and orientation of the block to prevailing wind is the determinant factors of creating ventilation corridors as well as passive cooling of urban areas. The major function of the urban ventilation corridor is breaking the urban heat island, improving urban airflow, increasing urban greening rate, and dividing the large area of urban space, and has a significance effect on urban ventilation (Guan et al., no date). So, designing of urban ventilation corridor to increase the city’s gaining of fresh air by deciding building size, orientation, and density is mandatory. The ventilation corridor is dependent on the spacing between buildings as shown in the image below in *Figure 2* that relates the horizontal spacing of the building versus the vertical height of the building that controls the moving and bouncing off air between buildings (Ding and Prasad, 2019).

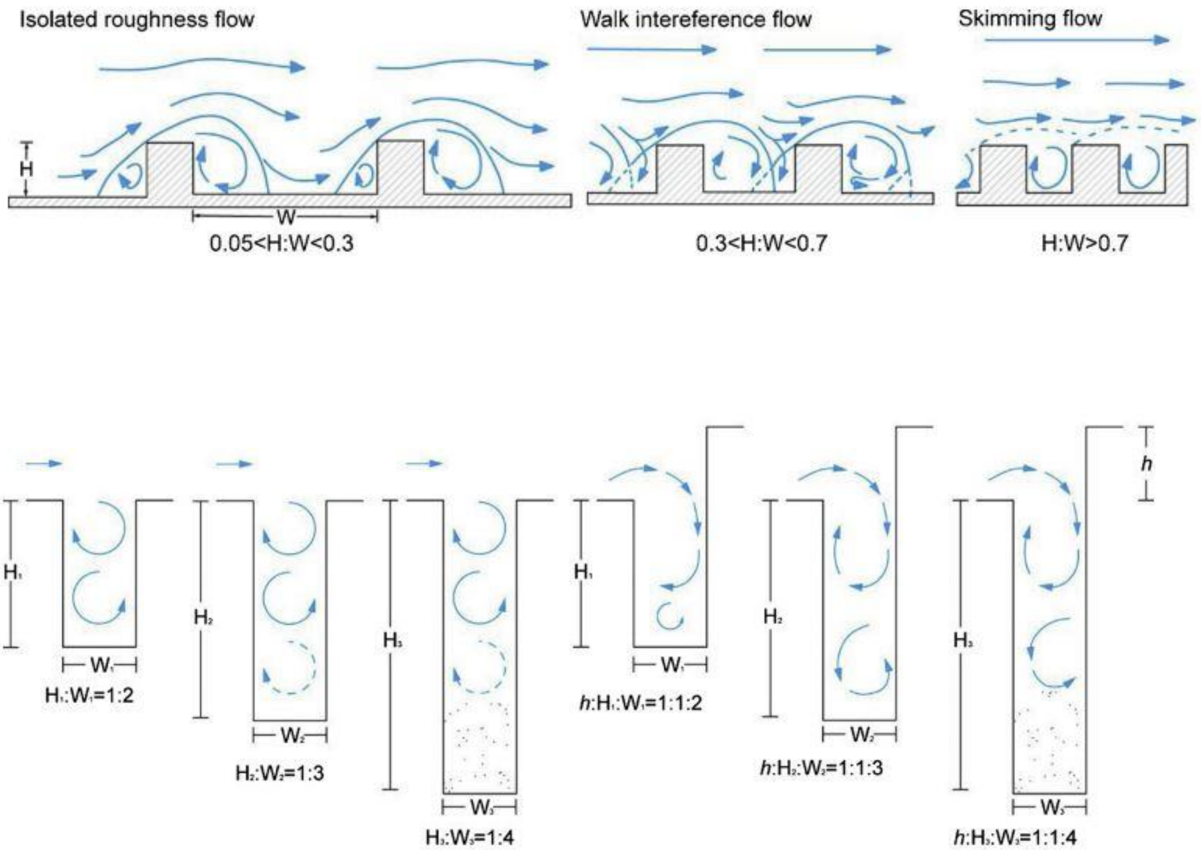


Figure 2: Air flow vortexes in idealized canyons when canyons are perpendicular to air flow *(Ding and Prasad, 2019)*

Enhancing the ventilation efficiency of high-density cities with large aspect ratios lies in adjusting street canyons parallel to the prevailing wind (Ding and Prasad, 2019). As shown in the *figure 3* below in hot and humid area block arrangement as stated in figure a is recommended and in figure b the ventilation is very low and also blocked by the building.

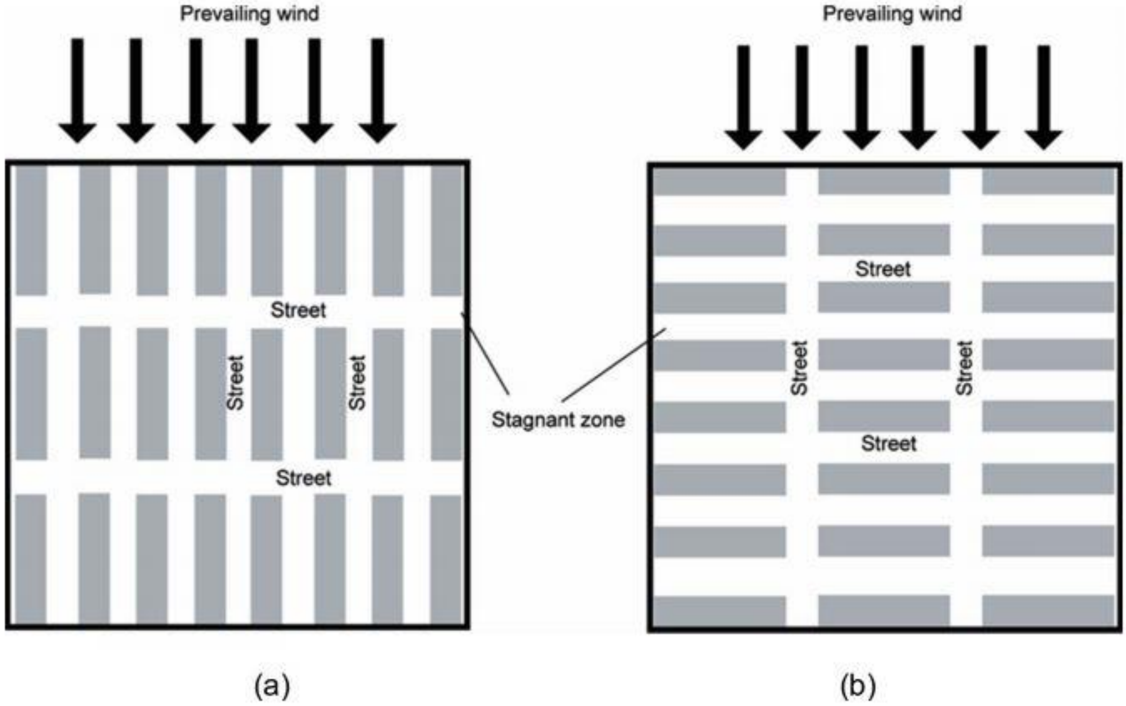


Figure 3: The pattern of a street canyon for ventilation: (a) recommended (b) not recommended (He, et al., 2019)

## 2.3 Natural ventilation for sustainable urban development

> *"Sustainability must be a part of our daily life. Its magical attraction forms a part of the homogeneous elements of the quintessential characteristics in any place on earth... crossing across immerse in hidden dimensions... floating around trying to let us discover its undeniable benefits (Session, 2005)".*

Climate change has a different effect on all over the world (Djukic et al., 2016). Urban growth harms the surrounding climate. Sustainable urban design is one of the contemporary concept to control the climate change in an urban area. Hot and hot humid area is the area that needs high attention on planning. In history the people use different methodology like wind chimney, short street, closed block (if the environment is harsh) and trees canopy (Baker, 2004). Urban energy efficiency in warm humid climates can be improved by encouraging multi-use building development to locate housing near places of employment and increasing population density with the introduction of slender, widely-spaced residential towers above the general 2 to 3 story development (Joubert, 1973).

### 2.3.1 Building Coverage Ratio (BCR)

BCR is a useful indicator describing urban heat island intensity and the impact of built-up areas on local wind velocity ratios (Jabarudin and Harith, 2012). Results of Yoshie's wind tunnel test on the wind situation of selected urban areas of Tokyo and Hong Kong have confirmed an inversely proportional relationship between gross BCR and wind velocity ratio ((Abd *et al.*, 2013). That is, the higher the gross BCR, the lower the observable wind velocity ratio. Furthermore, Abd *et al.*, (2013) have formulated a quantitative understanding of the impact of gross BCR on wind velocity ratio.

### 2.3.2 Building height (BH)

BH is a widely-used building morphology indicator in urban canopy models, in which different land-use types can be parameterized with different heights (Xu *et al.*, 2017). Numerical experiments and analytical models have confirmed that the impact of building height on wind speed is significant (Ying *et al.*, 2016). One case study conducted in Hong Kong indicated that controlling building heights effectively promote air ventilation in low/medium density areas (Xu *et al.*, 2017). Other than the impact on wind speed, building height information also helps to describe the thermal properties of different buildings to better model anthropogenic heat for urban climate studies (Salamanca et al., 2011).

### 2.3.3 Passive cooling

Climate is the major determinant for the formation and growth of a city and people to choose a place to live. Comfort is always an issue for selecting a place to live and production of surplus and industries. Climate-sensitive urban design has a major objective of creating comfort for a given by a means of passive or active methodology based on the climate conditions of the site area.

## 2.4 Thermal comfort and Urban Design

Thermal comfort is the balance between body heat and radiation. Thermal comfort is measured based on the climatic temperatures, surrounding material radiation, and convection with the body temperatures. If the surrounding temperature is above or below the comfort zone i.e, the human comfort zone is 18 - 25$^{o}$c and humidity from 20% to 80% indicated by (Victor olgay, 2015) bioclimatic chart, needs an introduction of different methodology to achieve comfort.

Thermal comfort is regarded as one of the most important contexts for sustainability which plays a great role in urban areas (Mayer, 2008).

> *"Thermal environment assessment is designed to acquire the cooling capacity of land at night-time by visualizing the difference between surface temperatures in the morning and evening, to show the intensity and distribution of urban heat island" (Liu et al., 2017*).

Lamarca et al. (2018), demonstrated that approximately 50% of human thermal comfort is dependence on adaption. Thermal comfort comprises several aspects which can influence significantly on a final personal judgment about the ambient environment. Human adoption is one of the most effective matters that affects thermal comfort. By definition, the term 'adaptation' is "the gradual decrease of the organism's response to repeated exposure to a stimulus, involving all the actions that make them better suited to survive in such an environment" ((Gan and Chen, 2012). However, for the newcomers and tourists' adaptation is not a planning solution to overcome thermal problems for a well-designed city, and the relationship between urban geometry and thermal comfort is by far less well understood and the number of studies is very few. On the other hand, urban design concepts for climate regulation do exist, which were gathered from a long history of building practice and further implemented in new projects. Yet, the quantitative assessment of these solutions is lacking or performed with weak methods ((Moonen *et al.*, 2012). The temperature of the surrounding is above or below the comfort zone the people use different methods to adapt to the prevailing climate. Based on the nature of human being adaptability, when the temperature is above comfort zone the people use cooling mechanism either in passive way or active way. When the condition rivers people use the heating mechanism to survive. In the urban areas the climate change and urban growth reversely proportional. To solve this problem, climate sensitive urban microclimate and design study must be considered.

## 2.2 Methods of Understanding Ventilation in city

### A. Wind Tunnel Test

Wind tunnel is a device used to investigate an interaction between solid body flows in wind tunnel by monitoring physical flow phenomenon and measuring aerodynamic quantities (Blocken et al, 2012). Wind tunnel test needs a physical modeling and fabrication of the machine. Even though, the tests area real and good in quality the wind tunnel test is very expensive and needs high energy. In Ethiopia only some university have wind tunnel test laboratory. Figure 4 below shows the wind tunnel room with model.

Figure 4 : wind tunnel test (Drew, 2008)

### B. Soft wares

### (i) CFD Application for urban density

Computational Fluid Dynamics software known as CFD tools are progressively being applied to the simulation of wind and fluid flow (Buccolieri and Hang, 2019). The software are applicable in different form as CFX, CFD, Ansys, Simscale plat form. The CFD software can process large are coverage with given numerical variables of temperature, wind, pressure, and fluid data. CFD simulations are performed over idealized building geometries. From these results, some of the physical parameters required as urban canopy parameterization (UCP) inputs are parameterized as a function of the urban morphology and meteorological conditions (Buccolieri and Hang, 2019). CFD can be applied at macro and micro scale urban design simulation of environmental and temperature radiation test of a building and city (Cheshmehzangi, 2016). The application of CFD for wind engineering are very vital to save time and energy to test by wind tunnel test.

### ii. Roughness Length and Sky View Factor (RL and SVF)

Urbanization may be thought of as covering the full spectrum of built-up areas from small rural communities to the true metropolis (Hansen, 1993). Any group of collective buildings altering the mean wind flow near the surface by increasing the roughness length.

Roughness length (RL) and sky view factor (SVF) are the main components to consider for classifying wind potential dynamics (Ren *et al.*, 2018). Table 2 below shows potential wind dynamics.

Table 2: Potential wind dynamics

| Classification | Description | Surface roughness Length (m) | Sky view factor |
|---|---|---|---|
| 1 | None or very low | > 1.0 | |
| 2 | low | (0.5 – 1.0) | < 0.65 |
| 3 | Moderate | (0.5 – 1.0) | ≥ 0.65 |
| 4 | Relative high | ≤ 0.5 | < 0.65 |
| 5 | High | ≤ 0.5 | ≥ 0.65 |

(Source: Ren *et al.*, 2018)

The RL is estimated based on the formula stated by Ren *et al.*, (2018)

$$\frac{Zd}{Zh} = 1.0 - \frac{1.0 - \exp[(-0.75x2\ x\lambda F)^{0.5}]}{(-0.75\lambda F)^{0.5}} \qquad (1)$$

$$\frac{Zd}{Zo} = (1.0 - \frac{Zd}{Zo})\ \exp\ (-0.4\ \frac{hu}{u} + 0.193) \qquad (2)$$

$$\frac{hu}{u} = \min\ [(0.0003 + 0.3\ x\lambda F)^{0.5}.\ 0.3] \qquad (3)$$

Where $\lambda F$ is windward area ratio with the values of 0.8 (Ren *et al.*, 2018), zh is 100m spatial resolution grid using building information.

SVF can directly show the potential urban heat island intensity. When the value of SVF is above 0.65, it has no impact on thermal load. Since urban ventilation has the effect of alleviating the urban heat island effect (Ren *et al.*, 2018).

SVF estimated and calculated

$$\text{SVF} = 1 - \sum_{i}^{n} sin\gamma i\ /\text{n} \qquad (4)$$

Where $\gamma$ is the influence of the terrain height angle on the azimuth angle i: n the number of calculated azimuth angel, and SVF is the normalized sky visual solid angle (Ren *et al.*, 2018).

The RL depends on the surface coverage land use of city. The RL and SVF processed by GIS plugins, Remote sensing Lidar and simulation software of solar radiation (Drew, 2008). The major challenge using RL and SVF is the need of detail data. That is difficult for large city.

## 2.4. Contextual Review

### 2.4.1 Potential of Natural Ventilation in Ethiopia

Natural ventilation, as the name implies, is a system using natural forces to supply fresh air for comfort and heat dissipation (Deriba, 2020). The natural ventilation source is wind. The wind blows from high pressure to low pressure of wind load. The warm air is less dense than cool air so it rises and creates a difference in pressure which in turn induces air movement, this phenomenon is called "the thermal buoyancy" and is sometimes referred to as "the stack effect"*(Olgyay, 2015).* Figure 5 shows the natural ventilation flow freely without any distraction physical body.

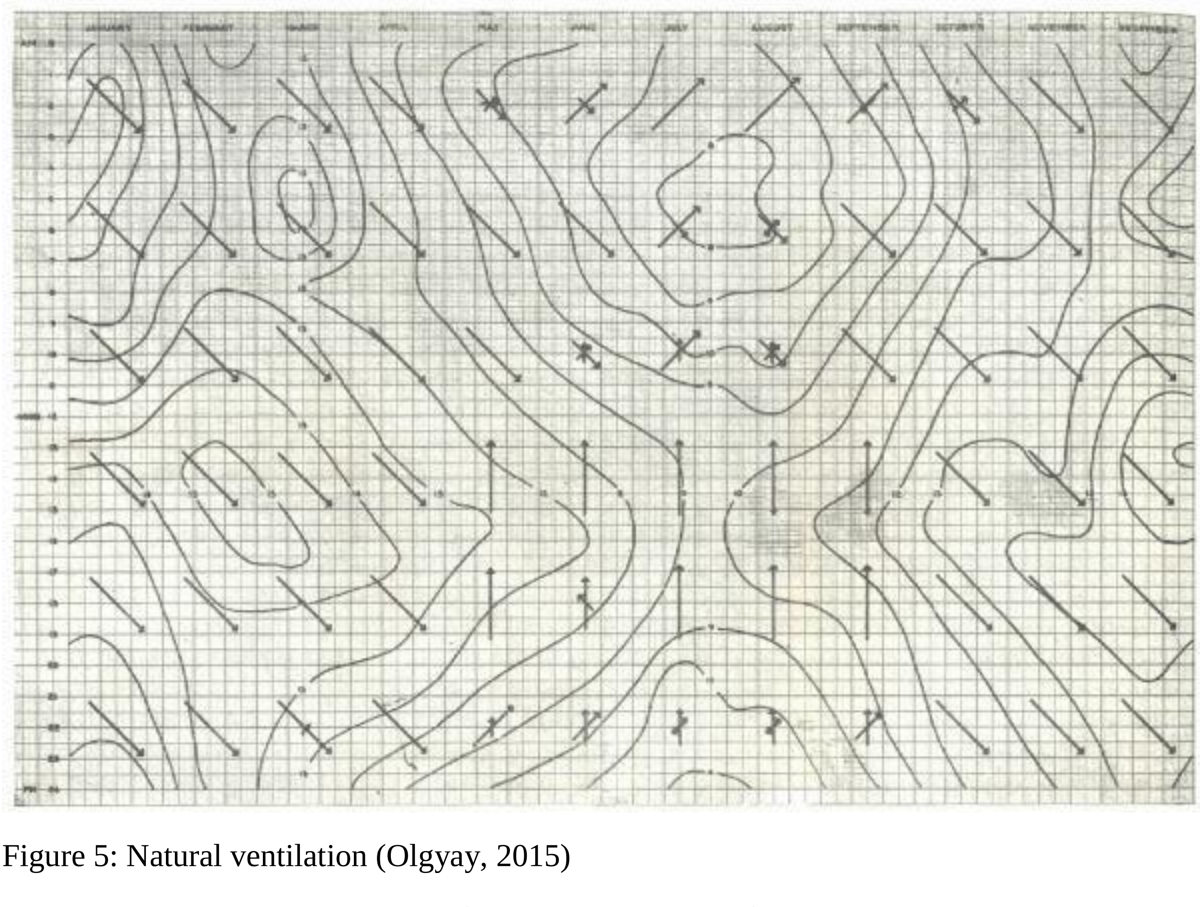


Figure 5: Natural ventilation (Olgyay, 2015)

Ethiopia have a good potential of natural ventilation from lake, river and mountainous topographic nature of the country. Figure 6 shows the wind potentials of Ethiopia.

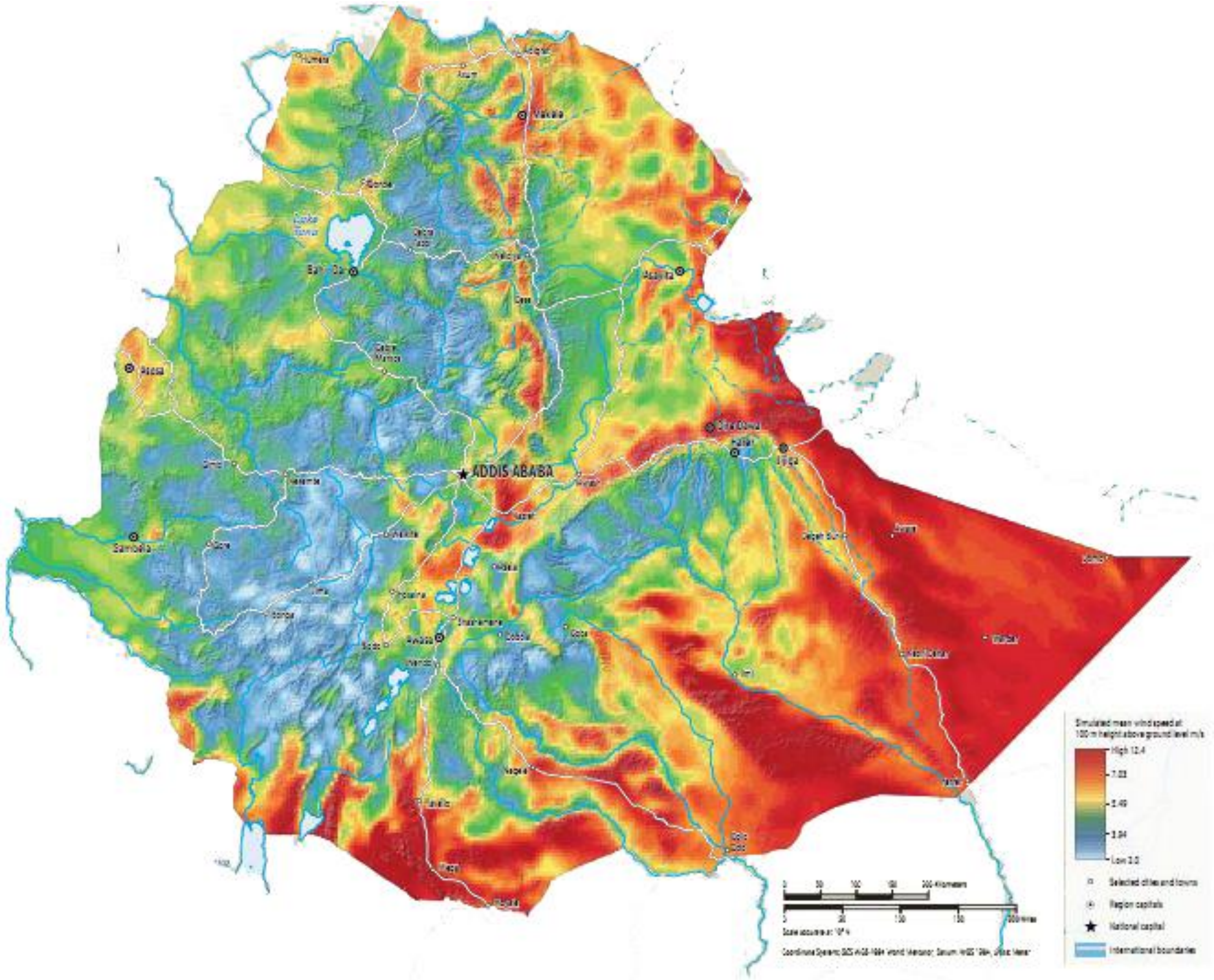


Figure 6: Wind speed of Ethiopia at 100m (World Bank group, 2016)

### 2.4.2. Wind Flow in Ethiopia

The wind flow in Ethiopia is dependent on the season. In different season the wind flow is changed. The dominating wind direction of country is from southeast it covers more than 500,000km$^2$ of the region (Deriba, 2020). Figure 7 below shows the wind direction map of Ethiopia.

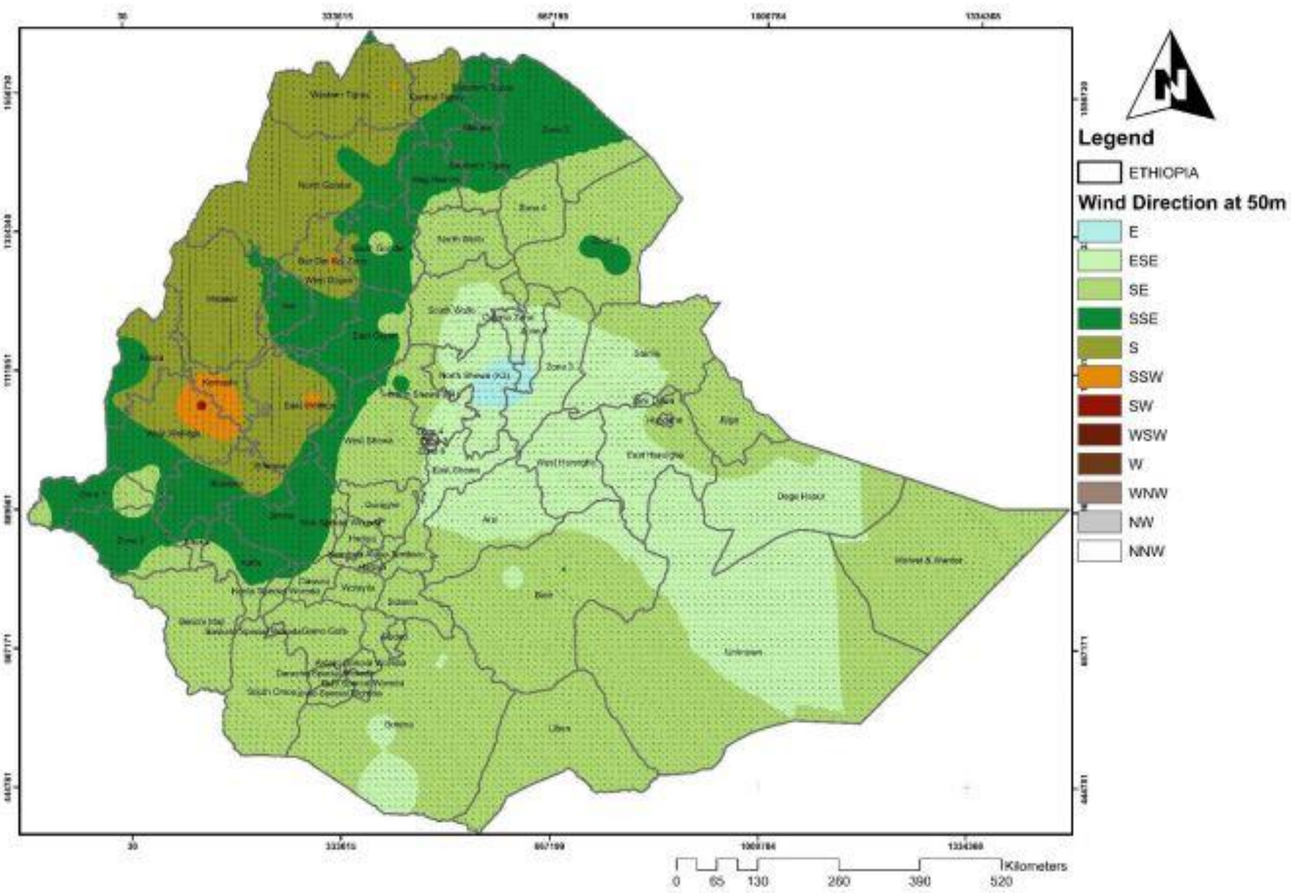


Figure 7: Wind direction map of Ethiopia (Deriba, 2020)

### 2.4.3 New Master Plan of Bahir Dar

Bahir Dar city has prepared a 50-year regional master plan as well as a 10-year structural plan in 2020 to date. The project is currently ongoing and presented two times. The project has proposed the regulation as shown below in the table.

Table 3: Bahir Dar structural plan proposal regulation

| Zone | FAR | | Set back from main road(m) | Maximum frontage (%) | | Road type | Building height(m) | |
|---|---|---|---|---|---|---|---|---|
| | Min | Max | | up to 4th floor | >4th floor | | Min | Max |
| Water front zone | 3 | 3.5 | 3 | 60 | 50 | <CS | 19 | 40 |
| | 3.5 | Free | 3 | 60 | 50 | ≥CS | | |
| Low density zone | 0.5 | 2.5 | 3 | 80 | 70 | <CS | .. | 19 |
| | 0.5 | Free | 3 | 80 | 70 | ≥CS | | |
| Medium density zone | 3.5 | 5 | 3 | 70 | 60 | <CS | 19 | 40 |
| | 5 | 7 | 3 | 70 | 60 | CS&SAS | | |
| | 5 | Free | 5 | 70 | 60 | ≥PAS | | |
| High density zone | 7 | 10 | 5 | 70 | 60 | <CS(30m) | 40 | 75 |
| | 7 | Free | 5 | 70 | 60 | ≥CS(30m) | | |
| Green | .. | 0.05 | .. | .. | .. | .. | .. | .. |
| Special | .. | .. | .. | .. | .. | .. | .. | .. |
| Aviation | .. | .. | .. | .. | .. | .. | .. | .. |

Source: (Bahir Dar City Administration, 2020)

The draft structural plan of Bahir Dar city regulation indicates in medium density development area near the lakeside has G+19 of minimum height with a building coverage (density) of 0.45 and the high-density development with a minimum height of G+40 with a density 0.50 t0 0.60 located the center of the city. Figure 8 shown the proposed land use of new master plan of Bahir Dar city.

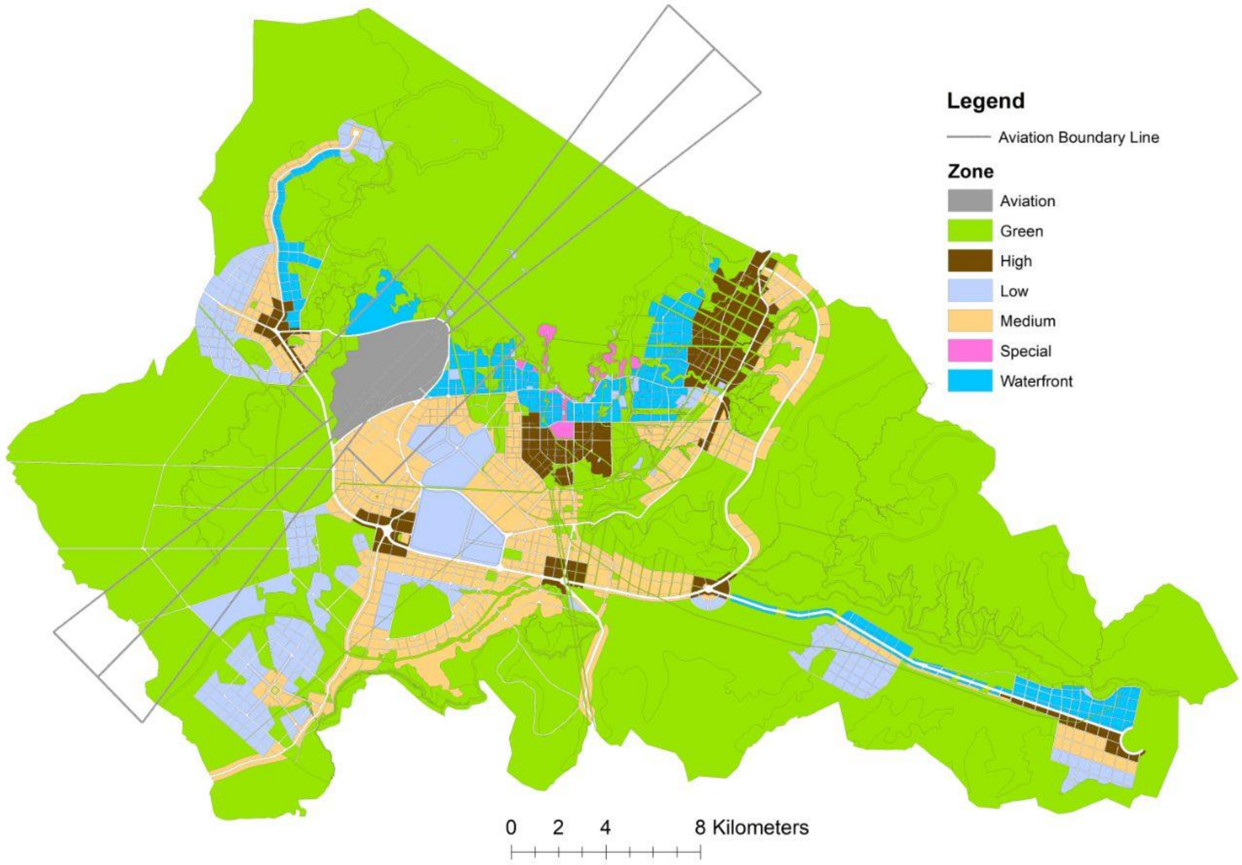


Figure 8: Bahir Dar structural plan source: (Bahir Dar City Administration, 2020)

# CHAPTER THREE

# MATERIALS AND METHODES

## 3.1 Study Area Description

Bahir Dar is a capital city of Amhara region, found in the northern part of Ethiopia. City of Bahir Dar located at the south side of Lake Tana and beginning of River Abay at 1,820 meters above sea level. It is located 11.59 latitude and 37.39 longitudes. The city is found in a tropical (highland) climate zone with hot climate conditions. Lake Tana and River Nile (Abay) makes the city important tourist destination and recreational city.

According to Meteo blue climate diagrams based on 30 years of hourly model simulations, the town temperatures vary from $8^0$C (the mean daily minimum for every month) to 36 $^0$C (the mean daily maximum for every month) and relative humidity is 58% from the data recorded 1961-2007 with the mean annual rainfall 1353mm.

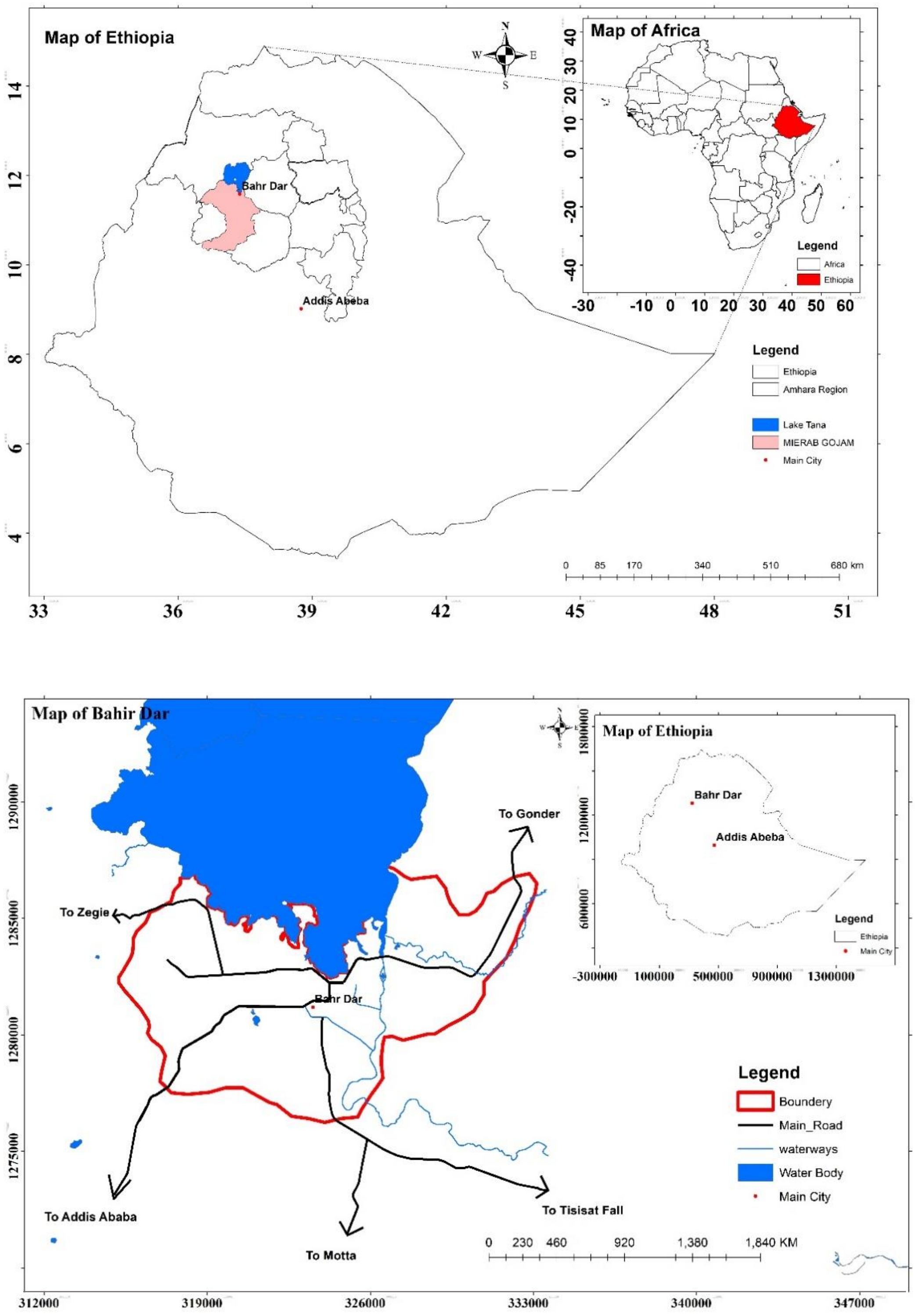


Figure 9: Location map

## 3.2 Research Design

The research design is over all process of research flows that integrates relevant component and data interpretation. This research design represents the process of this study paper. Figure 10 shows the combination of instrument and material used in the overall research process.

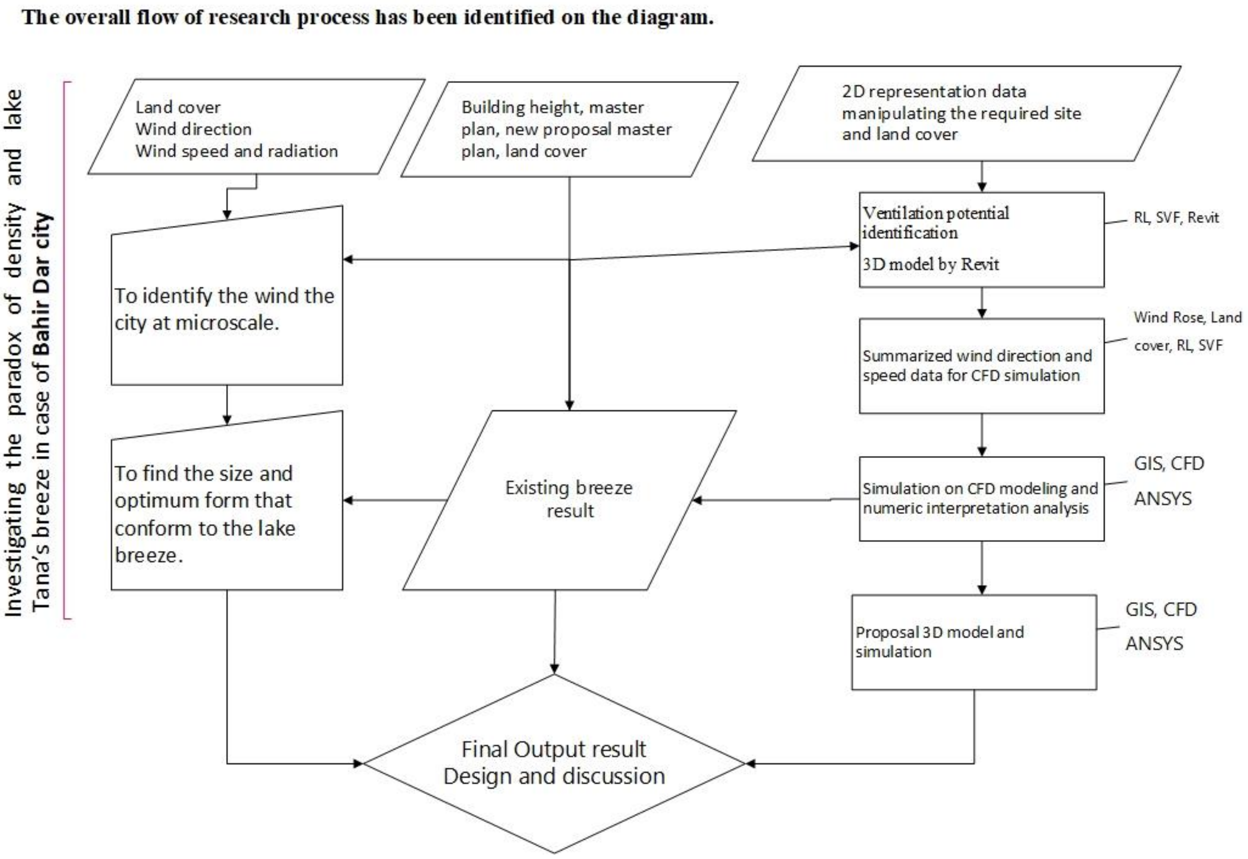


Figure 10: research design flow chart

### A summary of the methods

The methodology includes study area description, method of data collection, and method of data analysis and finally summarized in table 4.

Table 4: Methods and Methodology

| Objective | Data type | Data source | Methodology | Analysis |
|---|---|---|---|---|
| 1, To analyze current city breeze condition | Wind direction, wind speed, building height data, Land cover | Microclimate data from city municipal<br>From municipal master plan data | Calculating using RL, SVF and CFD simulation, GIS RL identification and grade ventilation potential | GIS based ventilation potential suitability, CFD simulation for ventilation |
| 2, To design the possible optimum density | New building design and density by Revit (3d) | Generate 3D model of the proposal | Modeling a 3d by rivet and import to CFD modeling and simulate by wind direction and speed summarized wind | GIS based suitability analysis to design optimum ventilation corridor design |

## 3.3 Methods of Data Collection

The data set used for this study were wind direction, wind speed, temperature, humidity and building height the weather data have collected from power Lars. Com, meteo blue, and weather spark historic data of 20 year started from 2000 to until now. The building height data have obtained from the municipal as well as on field observation.

## 3.3 Analytical Tools and Inputs Parameters

### 3.3.1 The Climate of Bahir Dar

The table below indicates that the 20-year climate data

*Table 5: Climate history of Bahir Dar city*: Source (Abebe, 2017)

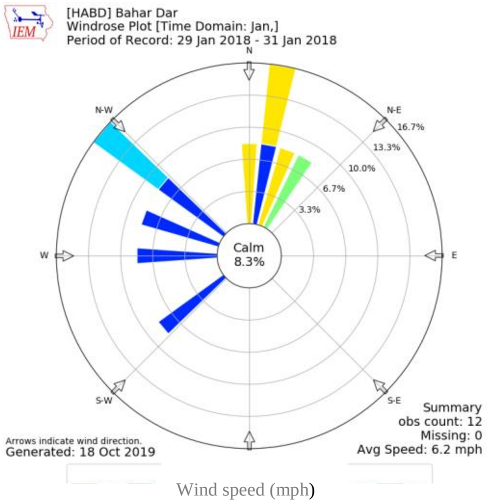
Climate data for Bahir Dar (1981–2010)

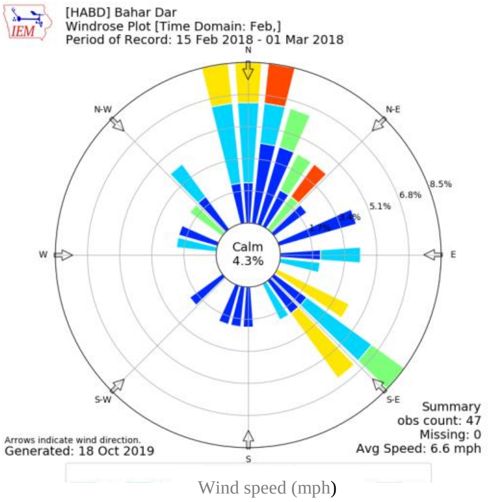
| Month | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | Avg |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Record High °C | 37 | 36 | 36 | 39 | 38 | 32 | 30 | 29 | 29 | 35 | 35 | 33 | 34 |
| Average high °C | 29 | 31 | 32 | 32 | 32 | 29 | 26 | 25 | 26 | 27 | 28 | 28 | 28.7 |
| Average low °C | 8 | 9 | 11 | 13 | 13 | 13 | 13 | 13 | 12 | 12 | 10 | 8 | 11.3 |
| Record low °C | 8 | 8 | 9 | 5 | 6 | 10 | 9 | 8 | 7 | 7 | 9 | 6 | 7.6 |
| Average rainfall mm | 2 | 2 | 12 | 28 | 80 |  |  |  |  | 87 | 12 | 6 | 19.1 |

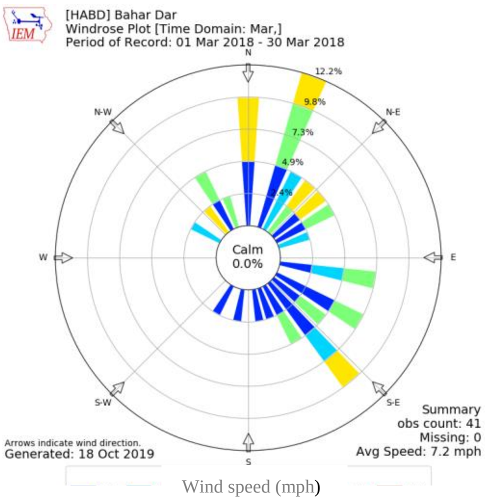
From the total season 3.6 months, from February 3 to May 24 are hot, with an average daily high temperature is above 29 °C. On these of three-month city have recorded hottest with a humid climate that is difficult for residence. The average hot and cold temperature indicates that the city needs active cooling and heating mechanisms to harmonize comfort base mechanisms.

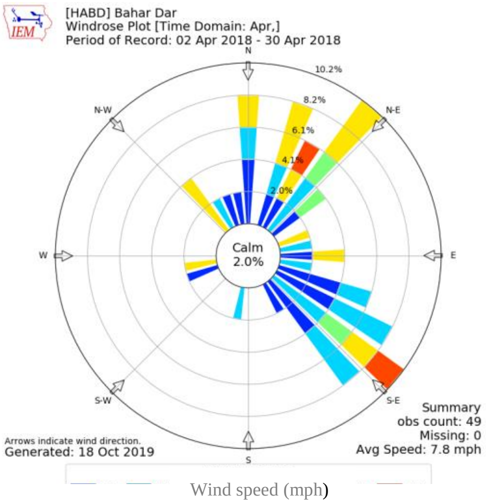
### 3.3.2 Wind and Comfort of Bahir Dar

Initially, the available local wind is collected from the (power spark weather.com) and power LARS of weather historic data. The wind direction in the season from September to November, east to west and from remain wind is from north side. The data set analyzed the period from December 2000 to December 2019. The data is set in the period of daily for 19 years. (‘Power_SinglePoint_Interannual_200001_2018’). The average speed of the wind blowing from the north is about 5.5m/s and the northwest wind is 4m/s of the average velocity of the period. The wind speed is vary from the ground to increase height. Figure 9 shows wind rose diagram of Bahir Dar for the data available of January, February, March, April, May, and June respectively. To generalize the wind direction of Bahir Dar city using wind rose Iowa Environmental Mesonet (IEM) is used. Figure 11 illustrates one year wind flow of 2018.









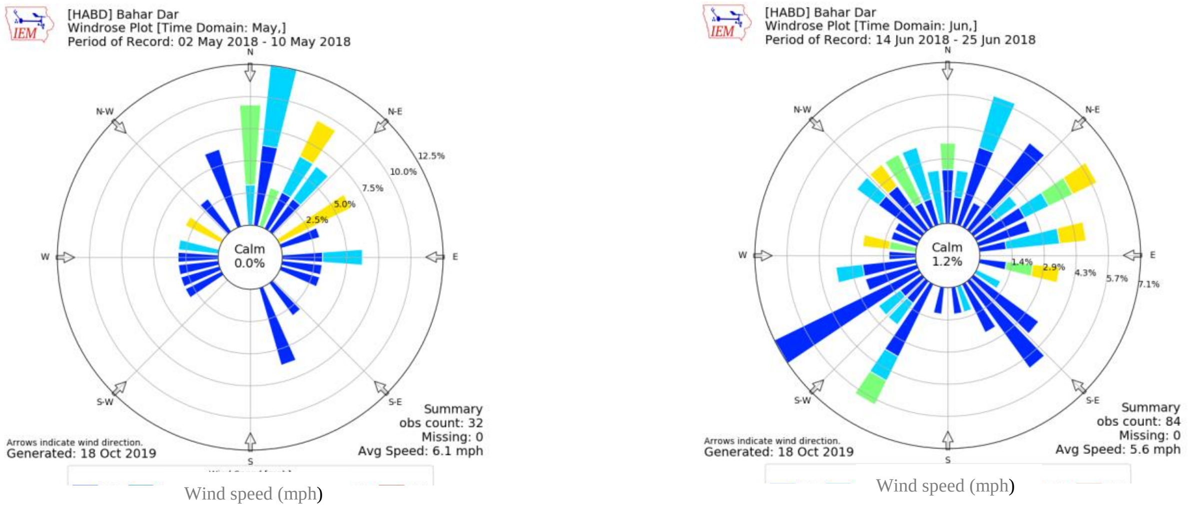


Figure 11: wind rose diagram of Bahir Dar

The prevailing wind direction of Bahir Dar is towards southeast during dry season and towards northwest during rainy. The main ventilation sources of Bahir Dar is monsoon wind that flows from Lake Tana to Bahir Dar. This main concern of study is the ventilation of dry season for city of Bahir Dar. Figure 12 shows the wind direction of Bahir Dar in winter and summer season.

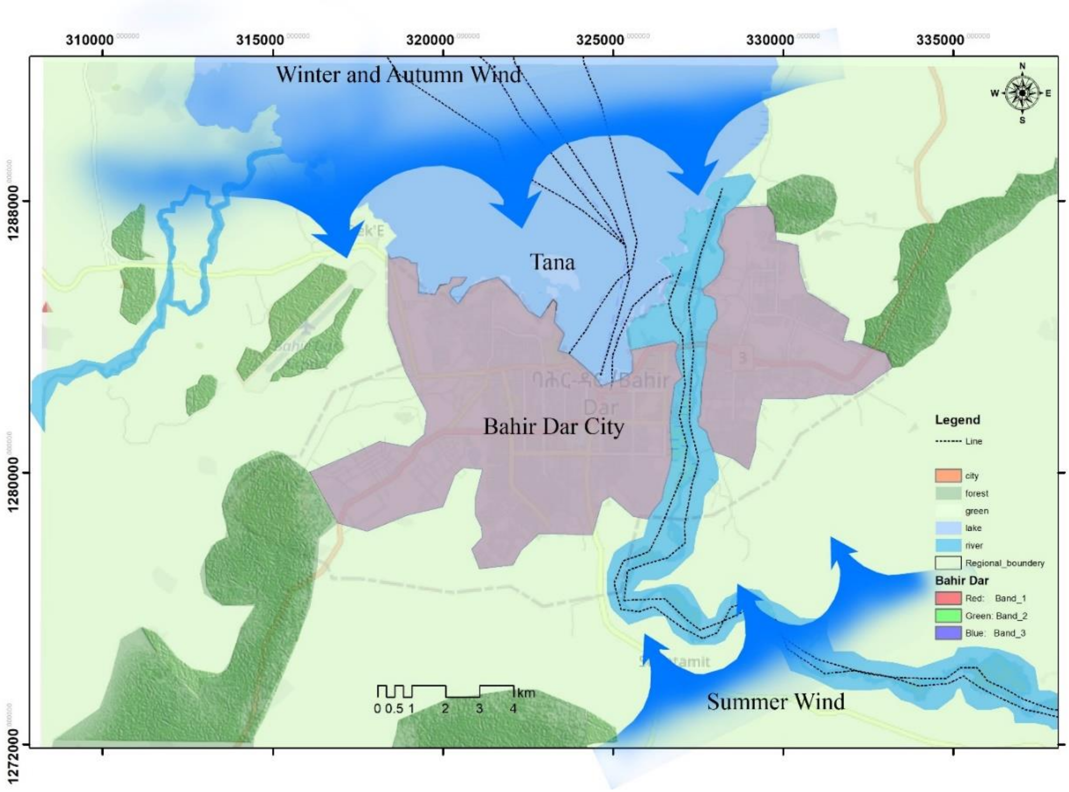


Figure 12: Wind source of Bahir Dar

The wind direction of the study area mostly blow within $165^0$ - $200^0$ degree of inclination. Figure 13 below shows dry season wind blow from Lake Tana to Bahir Dar. The dominance wind blows from North to South. The wind on these station point is 3.2m/s maximum and 2m/s minimum speed.

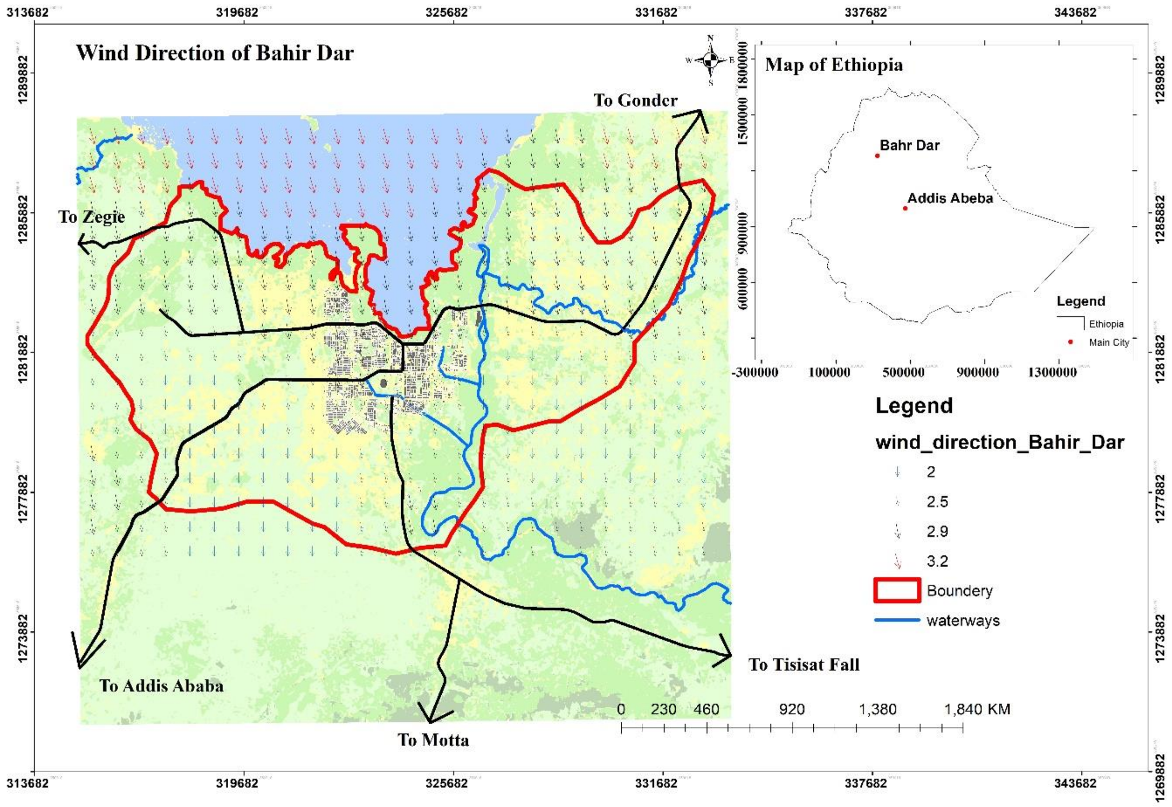


Figure 13: wind direction of Bahir Dar

### 3.3.3 Comfort Zone of Bahir Dar

Comfort zone is identified by bioclimatic chart. The chart developed by maximum temperature integrated with minimum humidity and minimum temperature with maximum humidity. Human comfort zone is described with temperature $18^0$C – $25^0$C with humidity of 20% - 80%. Bahir Dar city’s bioclimatic chart show that the climate from September to January are in comfort zone, from February to June are out from comfort zone and needs active and passive way of cooling mechanism and July and August are below comfort zone that needs passive way of heating mechanism. Generally Bahir Dar city environment condition needs passive way of cooling mechanism. Figure 14 shows the bioclimatic chart of Bahir Dar city.

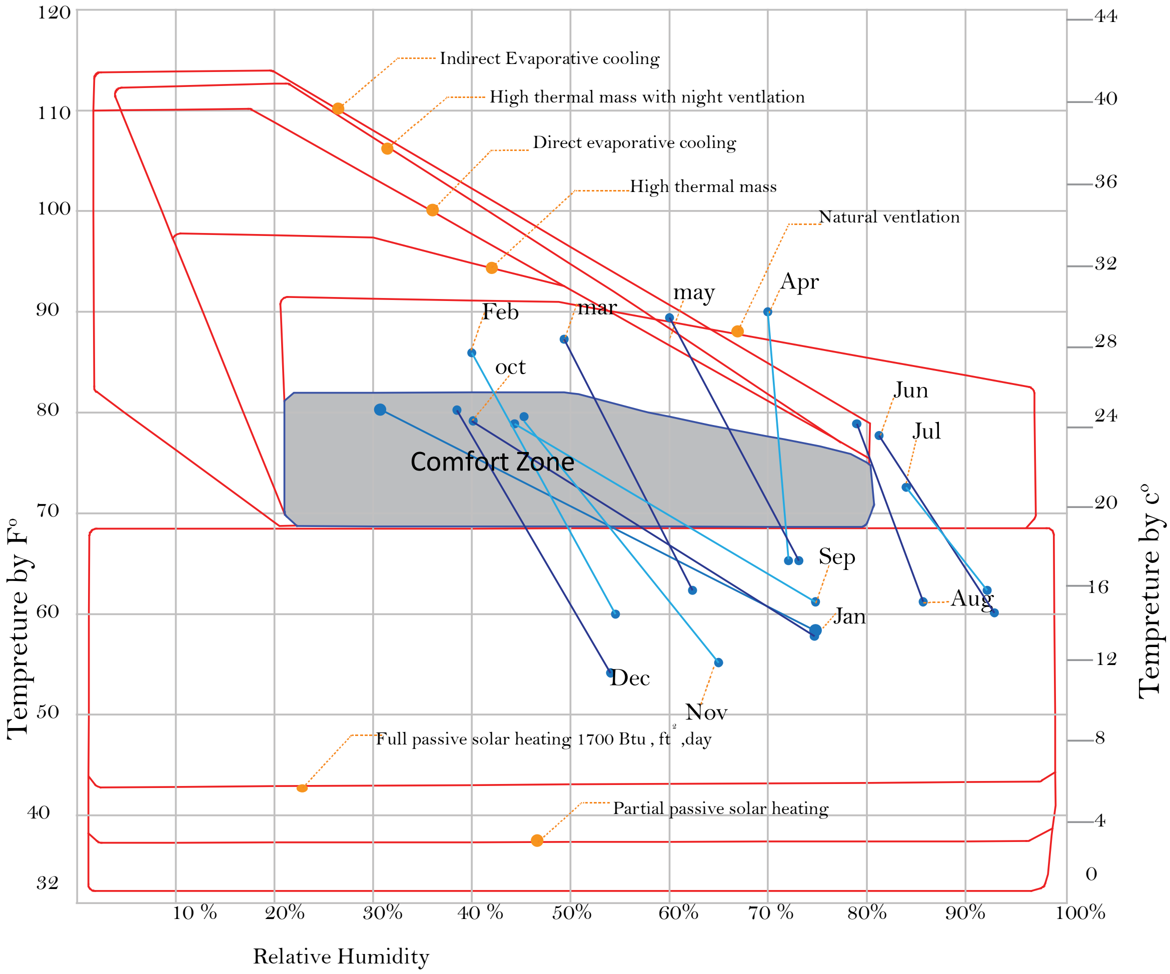


*Figure 14*: Bioclimatic chart of Bahir Dar city

### i. Land Use Land Cover of Bahir Dar

The land use land cover map of the study area identifies areas with buildings, forests, lakes, agricultural areas and bare land of the study area. Most of the land cover of Bahir Dar is greenery, wet land and settlements. The wetland is located in both the east and west part of the city. Figure 15 shows the land use land cover of Bahir Dar 2020 with remote sensing and GIS.

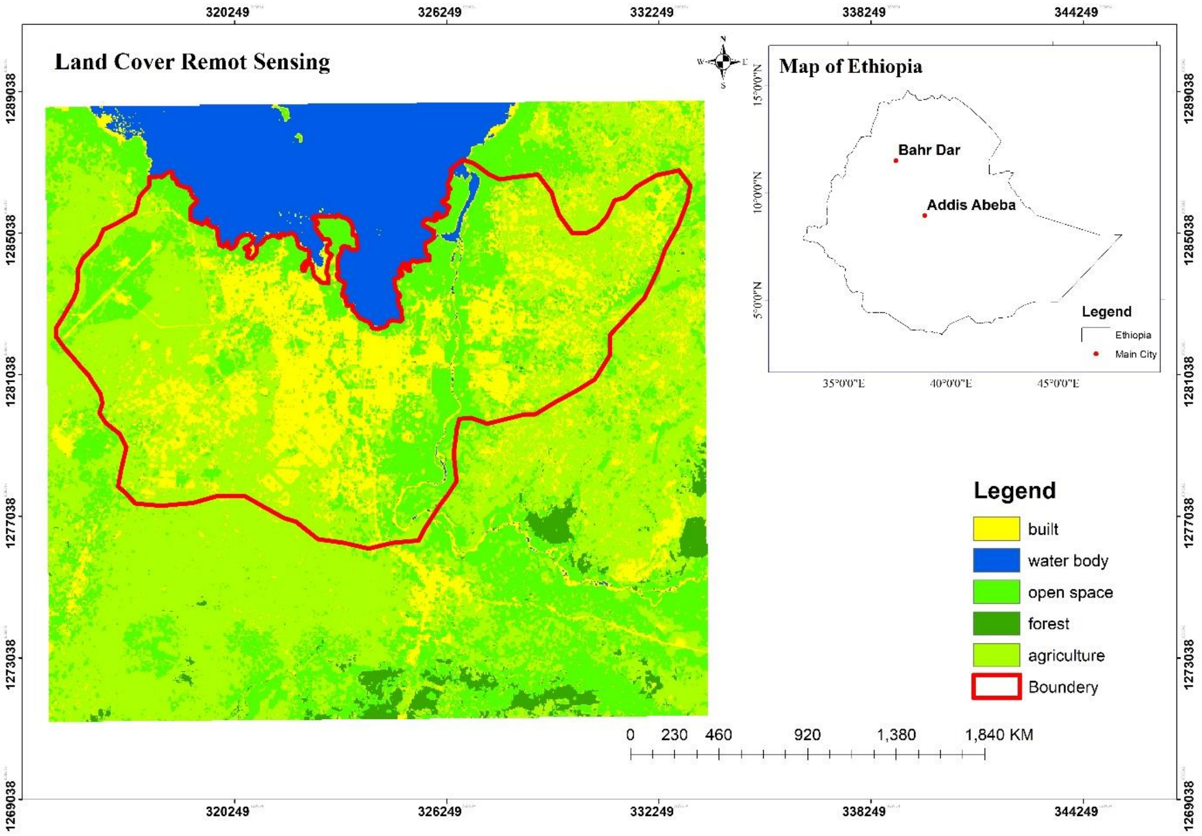


Figure 15: Land use land cover of Bahir Dar

The existing land cover in land sat 8 at 2020 of Bahir Dar shown below on table 6. The built environment of Bahir Dar covers 18% of the total land cover.

Table 6: Land Use Land Cover of Bahir Dar

| Land Use | Area (ha) | Percentage % |
|---|---|---|
| Built | 5846.31 | 18.02 |
| water body | 3673.89 | 11.3 |
| open space | 7882.29 | 24.3 |
| Forest | 723.24 | 2.23 |
| agriculture | 14303.07 | 44.1 |
| Total | 32428.8 | 100 |

### ii. Surface Temperature

Surface temperature shows the variation of urban heat island by land coverage types of the area. The water body surface temperature is lower than other land use cover temperature. Bahir Dar surface temperature is done by using remote sensing and GIS software. The surface temperature indicates the urban heat island difference between different land use types. Figure 16 shows the surface temperature of Bahir Dar city. As the map illustrates the surface temperature from the water body to build environment is around $10^{o}$C.

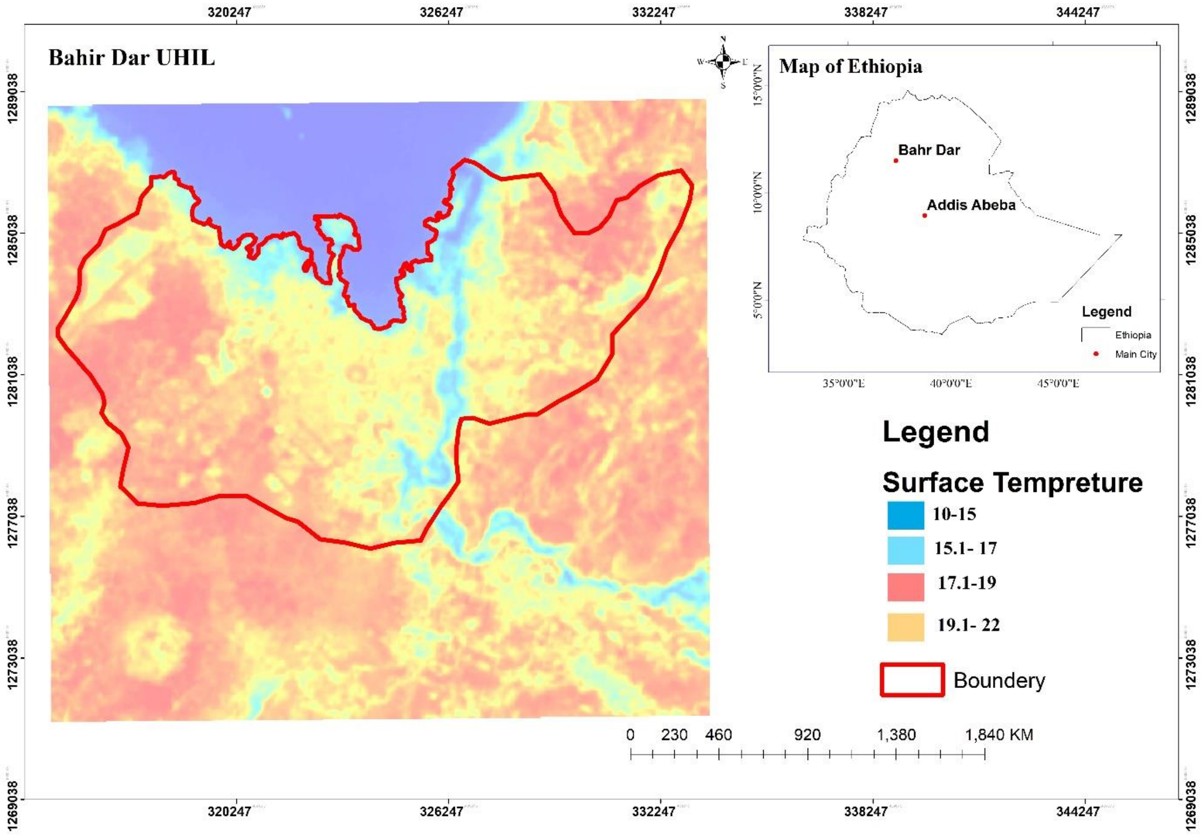


Figure 16: Surface Temperature of Bahir Dar

### 3.3.4 Ventilation Potentials of Bahir Dar

**i. Roughness Length (RL)**

Currently two methods are usually used to identify the RL: the meteorological observation method, which uses the measured wind data of a lux tower or meteorological station to calculate the RL, and the morphological method, which uses the geometric shape of the roughness element and its distribution density to calculate the RL (Liu *et al.*, 2016). The roughness length (RL) may be also estimated by CFD wind flow simulation of wind pattern. The study uses land sat file 8 and remote sensing land cover. The analysis and graphics interpretation is done by GIS focal statistics.

The first roughness that studied without development is terrain roughness. The terrain roughness is done using DEM model of resolution 30 meter.

Terrain roughness in GIS spatial data analysis – neighborhood – focal statistics minim, maximum, and smooth.

(Smooth mean - Minimum) (Maximum – Minimum) (3)

Figure 17 shows the terrain roughness of the study area. The roughness of water body calculated as zero and the slope less than three percent have low roughness and the slope above fifteen percent have high roughness values. The roughness of the study area is from 0.009 to 1 of minimum and maximum respectively. Low roughness area have high ventilation performance.

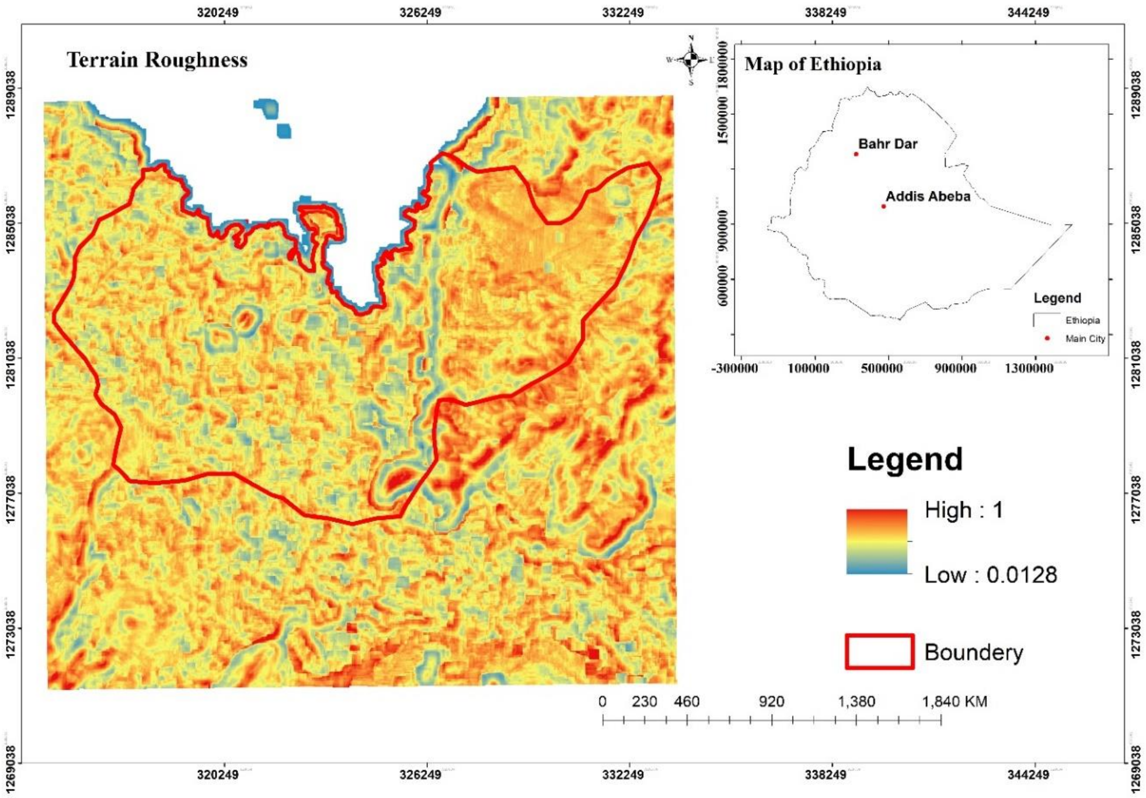


Figure 17: Roughness length (RL) of Terrain

Existing Land use roughness of Bahir Dar have done using the land cover map of land sat file. Focal statistics method have been used to generate the land cover roughness of the existing development. The built environment and forest have high values of roughness and the water body have low value of roughness (Figure 18). RL calculation

$$\frac{Zd}{Zh} = 1.0 - \frac{1.0 - \exp[(-0.75x2\ x\lambda F)^{0.5}]}{(-0.75\lambda F)^{0.5}} \qquad (4)$$

Zd is RL or zero desplacement, Zh is building information 100m high resolution , $\lambda F$ wind ward area ratio of urban building. The data is collected by cadasteral of all building coverage. In this study the cadasteral data collection is not used. According to the research finding of Liu *et al.*, (2016) building coverage of the peak value is 0.3 to 0.4. this study use 0.4 coefficient for calculating RL.

$$\frac{Zd}{zh} = 1.0 - \frac{1.0 - \exp[(-0.75x2\ x0.4)^{0.5}]}{(-0.75x0.4)^{0.5}} \quad = 0 \text{ to } 0.12 \qquad (5)$$

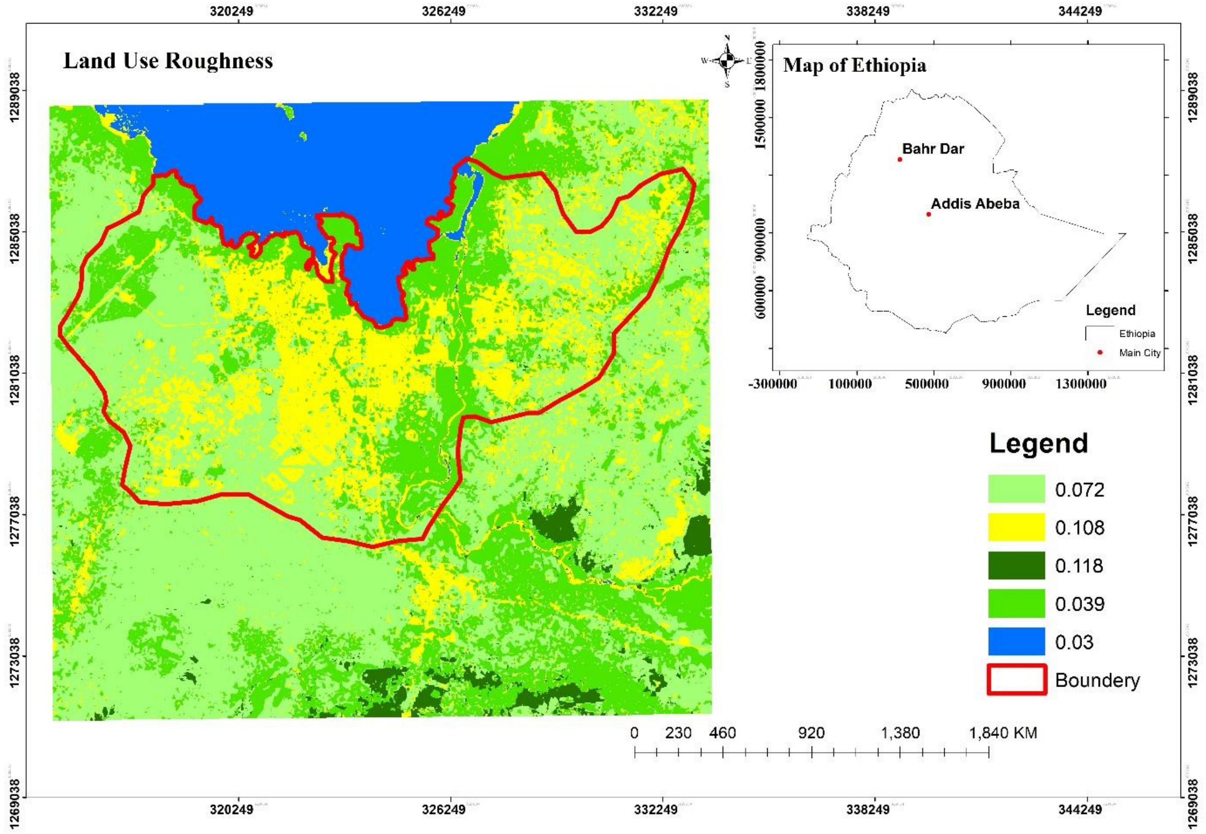


*Figure 18*: Roughness Length map

### ii. Sky View Factor (SVF)

The SVF is a numerical value describing the 3D urban form, and it reflects the different geometrical forms of urban street channels; influences the surface energy balance relationship; changes the local air circulation; acts as the comprehensive index for planning urban streets, communities and other local features; and serves as a reference for scientific urban planning (Liu *et al.*, 2016). To calculate sky view factor (SVF) 30 meter resolution DEM and building raster have been use. SAGA GIS have been use to produce graphical SVF calculation mapping. The SVF of Bahir Dar city with surrounding area are 0.13 to 1.5 from lowest to highest view. SAGA GIS mapping tools are used with 100m resolution factor DEM of Bahir Dar city. Figure 19 shows the SVF of study area.

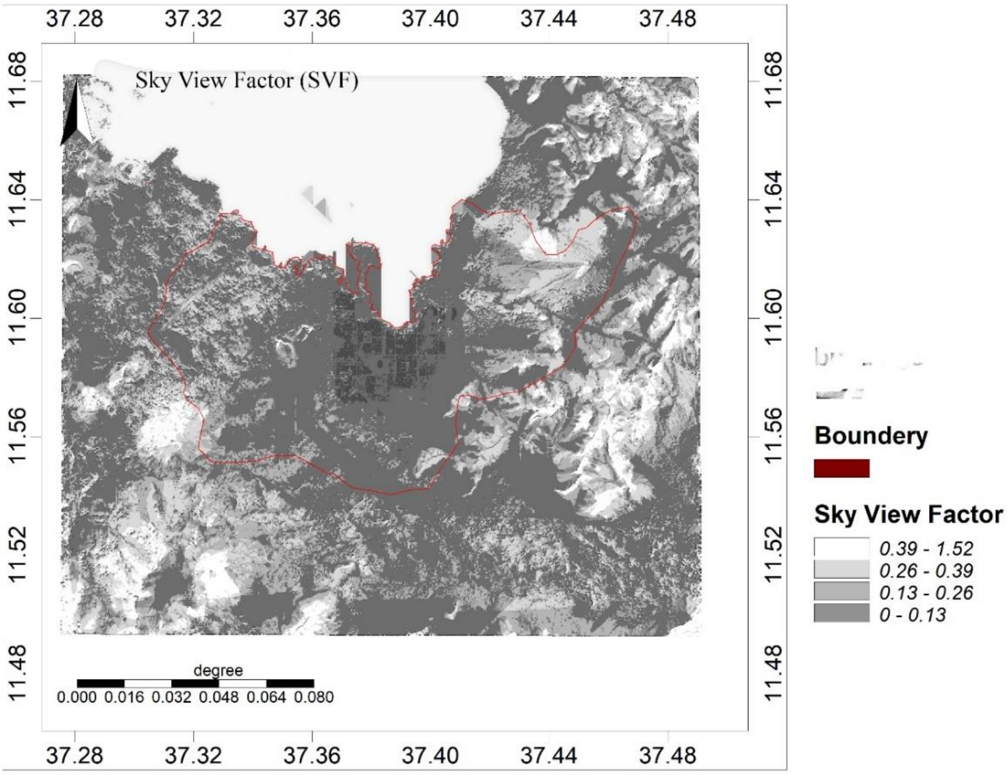


Figure 19: SVF map of Bahir Dar

### i. Grading the Ventilation Potential

In the study of SVF with respect of urban heat island effect urban area (Liu *et al.*, 2016) conclude that the SVF influenced the urban heat island intensity significantly. The author defined the SVF factor 0.65. Because the SVF factor exceed this value ventilation alleviates the heat island. The RL of the author 0.5. Set RL< 0.1 in highly ventilated area, such as water body and small grass. This study define the upper limit of RL > 0.6 for high density area and the lower limit is 0.1 for high ventilated area. Table 7 shows ventilation potential grading.

Table 7: Grading ventilation potential

| Type | Grade I | Grade II | Grade III | Grade IV | Grade V |
|---|---|---|---|---|---|
| Roughness length | >0.6 | 0.1 – 0.6 | ≤0.1 | 0.1 – 0.6 | ≤0.1 |
| Sky view factor | - | 0.75- 0.9 | 0.75- 0.9 | ≥0.9 | ≥0.9 |
| meaning | no | General | Relatively High | High | Very high |

### ii. Ventilation potential using CFD

CFD Software performs the ventilation performance and wind shadow of city with 3D ways. This study conducts the ventilation of current high rise building height greater than 15 meter above the ground. The existing wind flow pattern at 15m is slightly medium intensity and the breath is a medium and in some area that high density of the building that the ventilation is low as the simulation below indicates the orientation of the street, as well as the building density, decreases the breath of the city. Figure 20 shows the ventilation performance of Bahir Dar above 15 meter from the ground.

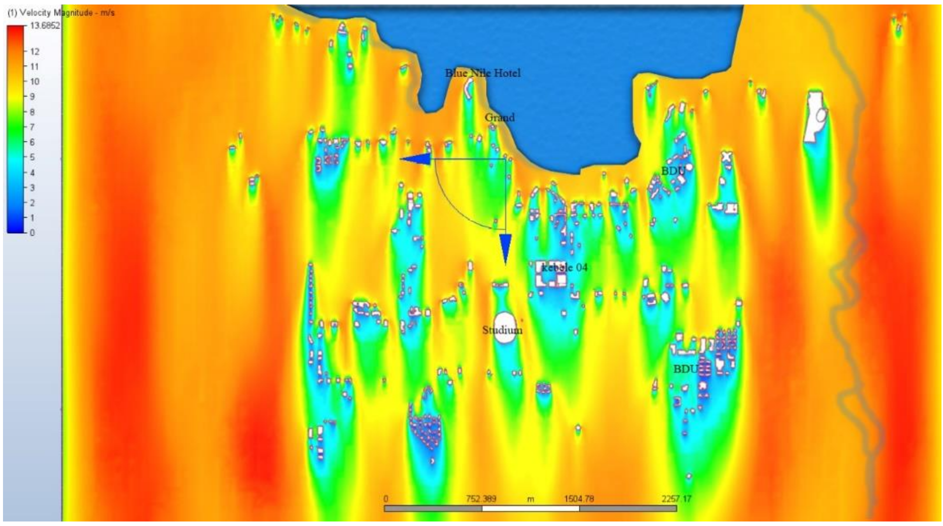


Figure 20: Ventilation performance at 15m

# CHAPTER FOUR

# RESULTS

## 4.1 Estimating the ventilation potential at Bahir Dar city

Figure 21 shows the ventilation potential distribution of Bahir Dar city from 2020 DEM 30m resolution. The ventilation potential in the Northern and Southern side of Bahir Dar plain is very high, and there is no ventilation blocks before construction. Dry season wind flows from North to South is very suitable to cool Bahir Dar. The blue arrow shows the main city breeze potential without construction. The main source of fresh air in dry season is from Lake Tana. In the hot season, February, March, April and May Bahir Dar is breezed by Lake Tana. The result shows that, low development area of Bahir Dar has high ventilation performance.

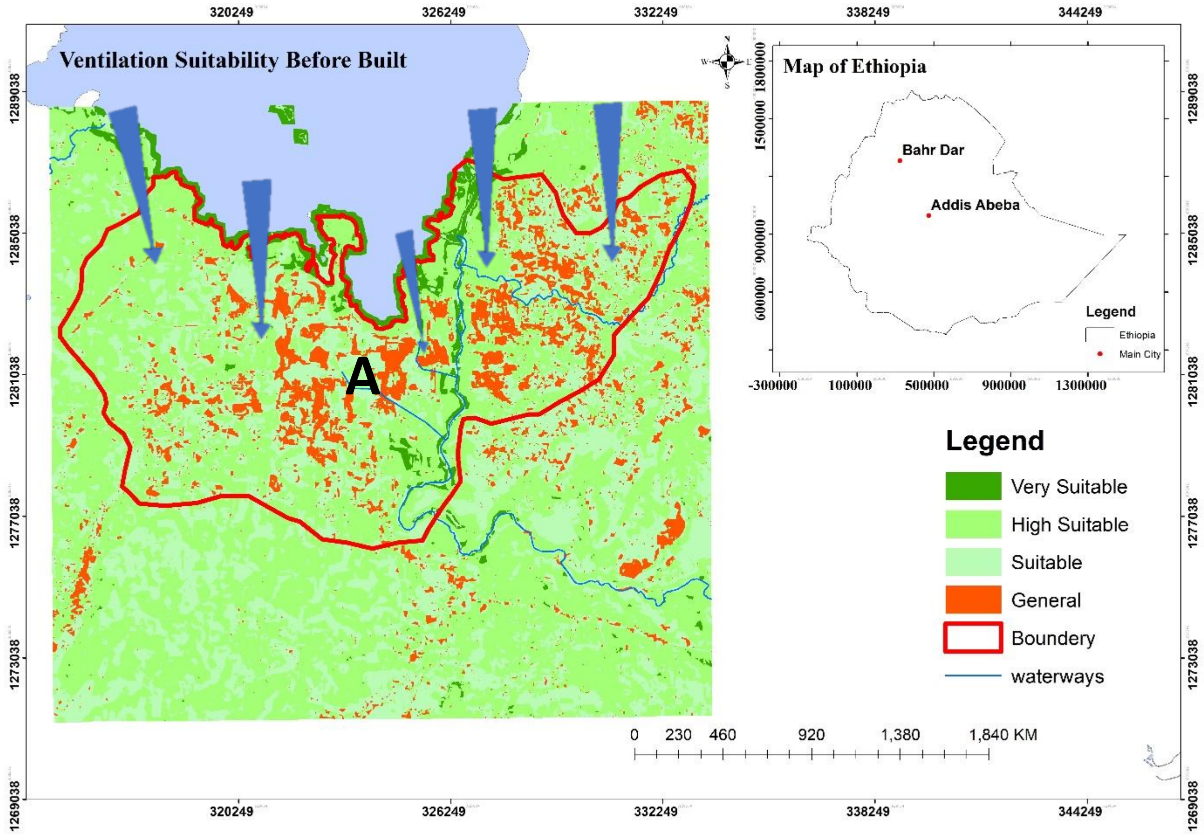


Figure 21: Ventilation potential without development

Figure 22 shows the ventilation potential distribution of Bahir Dar city existing development 30m resolution. The ventilation potential in the northern side of Bahir Dar plain is very high, and there is no apparent ventilation potential in relatively dense building area. In Figure 22 shows the ventilation potential in place **A** relatively low. Place **A** development will not only influence the ventilation environment but may also prevent northern air flow from entering to the southern part of Bahir Dar city. Place **A** scores high roughness 0.5 of building roughness and relatively medium SVF 0.7 with low raise building height.

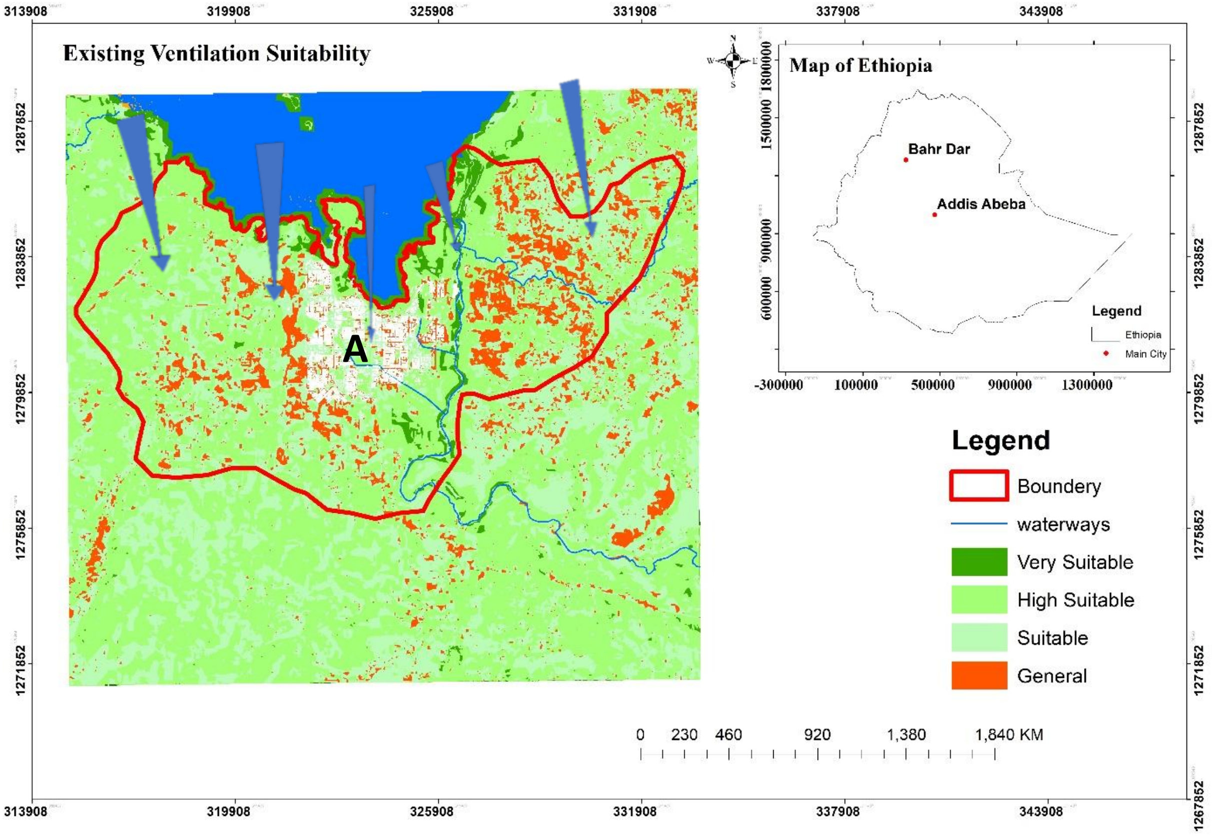


Figure 22: Ventilation potential in existing development

## 4.2 Estimating the ventilation potential of new master plan proposal of Bahir Dar

The city proposed new structure plan that increase the built up area twice from the existing built area. Land use proposal and density regulation have been used to estimate the ventilation potential of the new proposal of Bahir Dar city by the research. Figure 23 shows the ventilation potential of Bahir Dar city new structure plan proposal. The ventilation potential from the southern part of the city reduced significantly. Urban agricultural land in the southern part of the city changed medium density urban development area with a density 0.45 and the inner part of the city proposed with high density high raise building height. The maximum building height proposed is G+ 75. Place **A** in the figure shows existing built area that changed to high density development that reduce the ventilation potential, not only that the development blocks the wind flow the places located in **C** and **D** on the figure. Place **B**, **C**, and **D** are additional proposed place from the existing city boundary. The ventilation potential index is low 0.3 as compared from the existing ventilation potential of Bahir Dar.

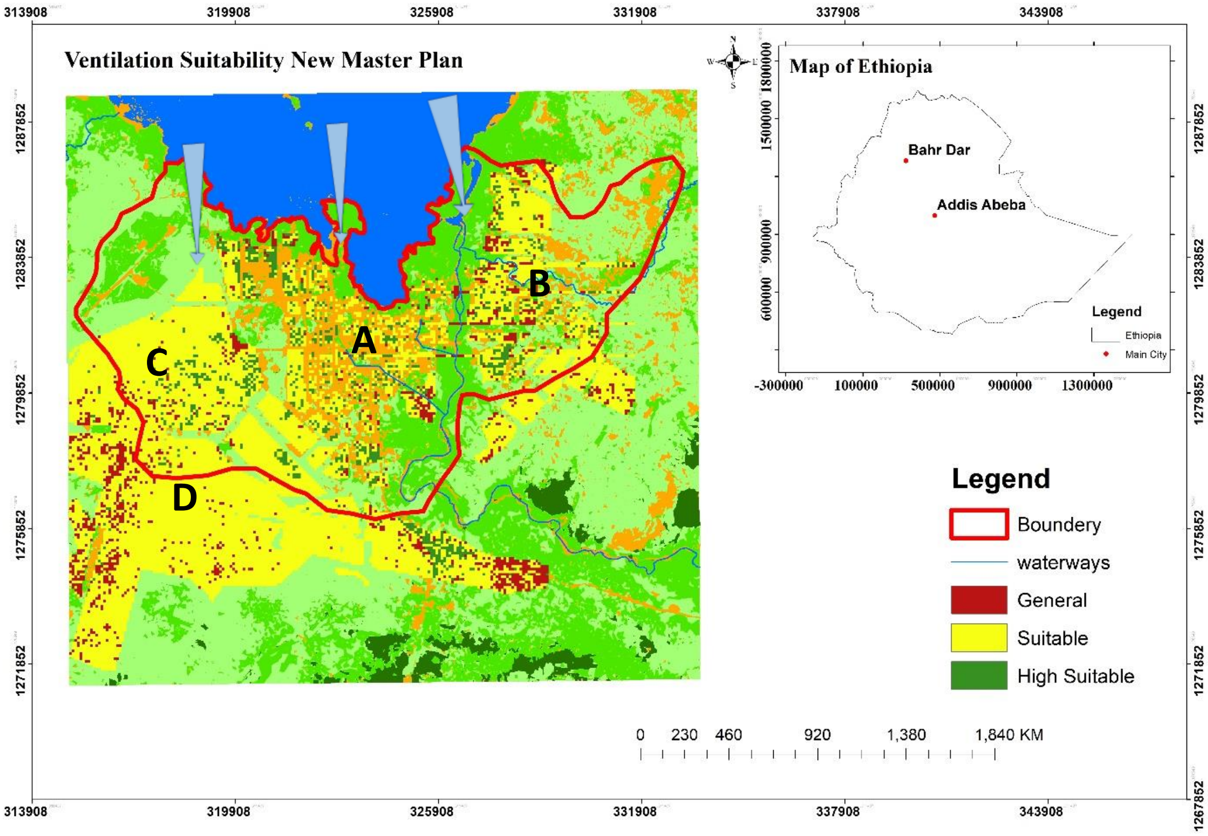


Figure 23: Ventilation potential of new structural plan Bahir Dar

## 4.3 Optimum Ventilation Corridor Design

Urban ventilation corridors are formed by ecological buffer zones, greenbelts, roads, rivers, parks and green spaces (Ren *et al.*, 2018). The design of optimum ventilation corridor of Bahir Dar is design by the ventilation criteria of high ventilation performance of the city.

Calculation of building height decision by SVF

$$SVF_{canyon} = \cos(\operatorname{atan}(2.H/W)) \tag{6}$$

H= Building height

W= Street width

Table 8 shows the sky view factor of master plan regulation and different building height with constant street width. The red line shows the minimum SVF without considering building set back. Right side from red line is the maximum building height and minimum SVF result.

Table 8: SVF by changing building height

| Street width (m) | Building Height and SVF | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | H1 (m) | SVF | H2 (m) | SVF | H3 (m) | SVF | H4 (m) | SVF | H5 (m) | SVF |
| 40 | 210 | 0.1 | 120 | 0.16 | 80 | 0.24 | 60 | 0.32 | 40 | 0.45 |
| 30 | 120 | 0.12 | 60 | 0.24 | 48 | 0.3 | 40 | 0.35 | 30 | 0.45 |
| 25 | 120 | 0.1 | 60 | 0.2 | 40 | 0.3 | 30 | 0.38 | 15 | 0.64 |
| 20 | 90 | 0.11 | 30 | 0.32 | 20 | 0.45 | 15 | 0.55 | 9 | 0.74 |
| 15 | 60 | 0.12 | 30 | 0.32 | 15 | 0.45 | 9 | 0.59 | 6 | 0.78 |

Figure 24 shows the SVF and building height relationship that, when building height increase SVF decrease. For Bahir Dar minimum SVF factor with optimum density without considering set back of building is allowed 0.2.

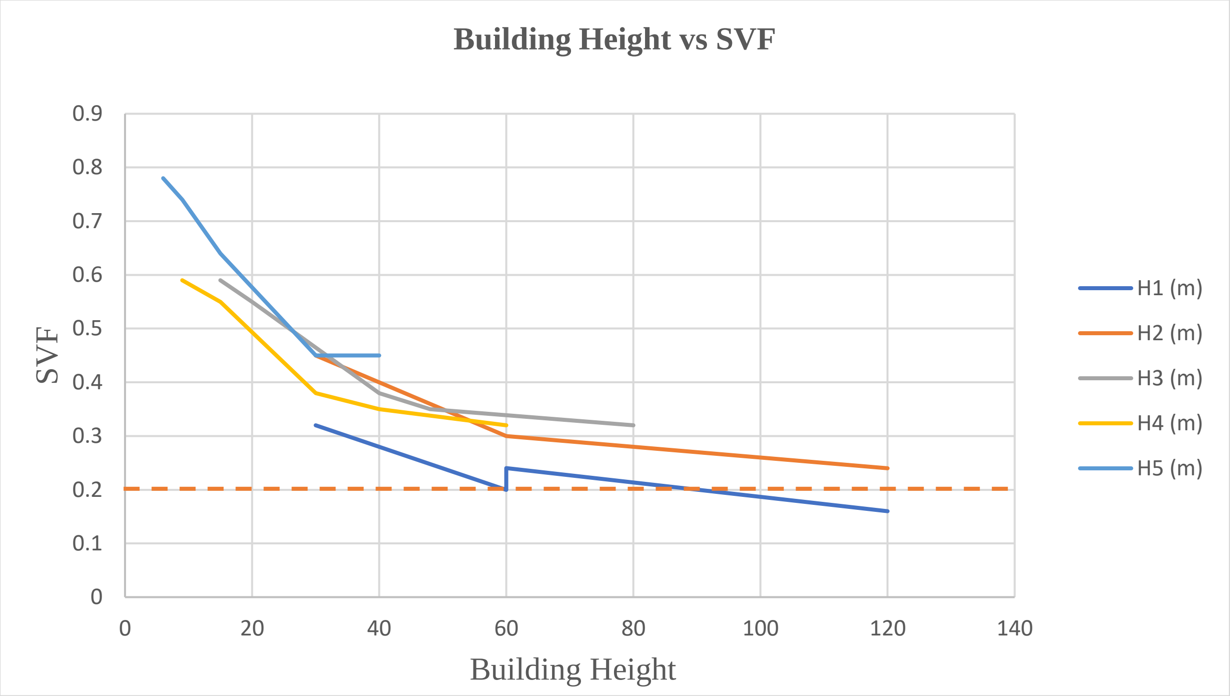


Figure 24: SVF and building height relationship

Table 9 shows the maximum building height according to minimum SVF for corresponding street width of Bahir Dar.

*Table 9: Optimum density design by SVF*

| Street width (m) | building height maximum (m) | SVF |
|---|---|---|
| 40 | 80 | 0.24 |
| 30 | 60 | 0.24 |
| 25 | 60 | 0.2 |
| 20 | 50 | 0.2 |
| 15 | 40 | 0.2 |

The suitability design is done maximum built density 55%, maximum roughness length 0.6, and sky view factor 0.25 and minimum ventilation corridor of 100m width to get the best possible ventilation corridor. Table 10 shows the suitability criteria for optimum density design of Bahir Dar ventilation corridor.

Table 10: Criteria to get optimum ventilation corridor

| Type | Minimum | Maximum |
|---|---|---|
| Density | 40% | 55% |
| Roughness Length | 0.1 | 0.6 |
| Sky view Factor | 0.25 | 0.90 |
| Ventilation corridor length | 100 | - |
| Ventilation corridor obstacle | - | 15% |

The optimum ventilation corridor design of Bahir Dar used multiple criteria such as; (RL, SVF, density, ventilation corridor length and ventilation corridor obstacle) to analyze suitability of ventilation corridor design by using GIS software. The ventilation performance index of the final design is 0.6 after suitability analysis conducted. The ventilation corridor design by considering the winter wind and peak temperature value. The major city breeze is level one ventilation corridor shown by green arrows. Level one ventilation corridor design by connecting the main open space, water body and city parks as a buffer for the city. Ventilation corridor two is designed connecting small public space with Major Street of Bahir Dar. The dot grid polygon shows the ventilation obstruction corridor of city built environment (Figure 25). Inside this polygon level three ventilation have been design by greenery and local road of the city.

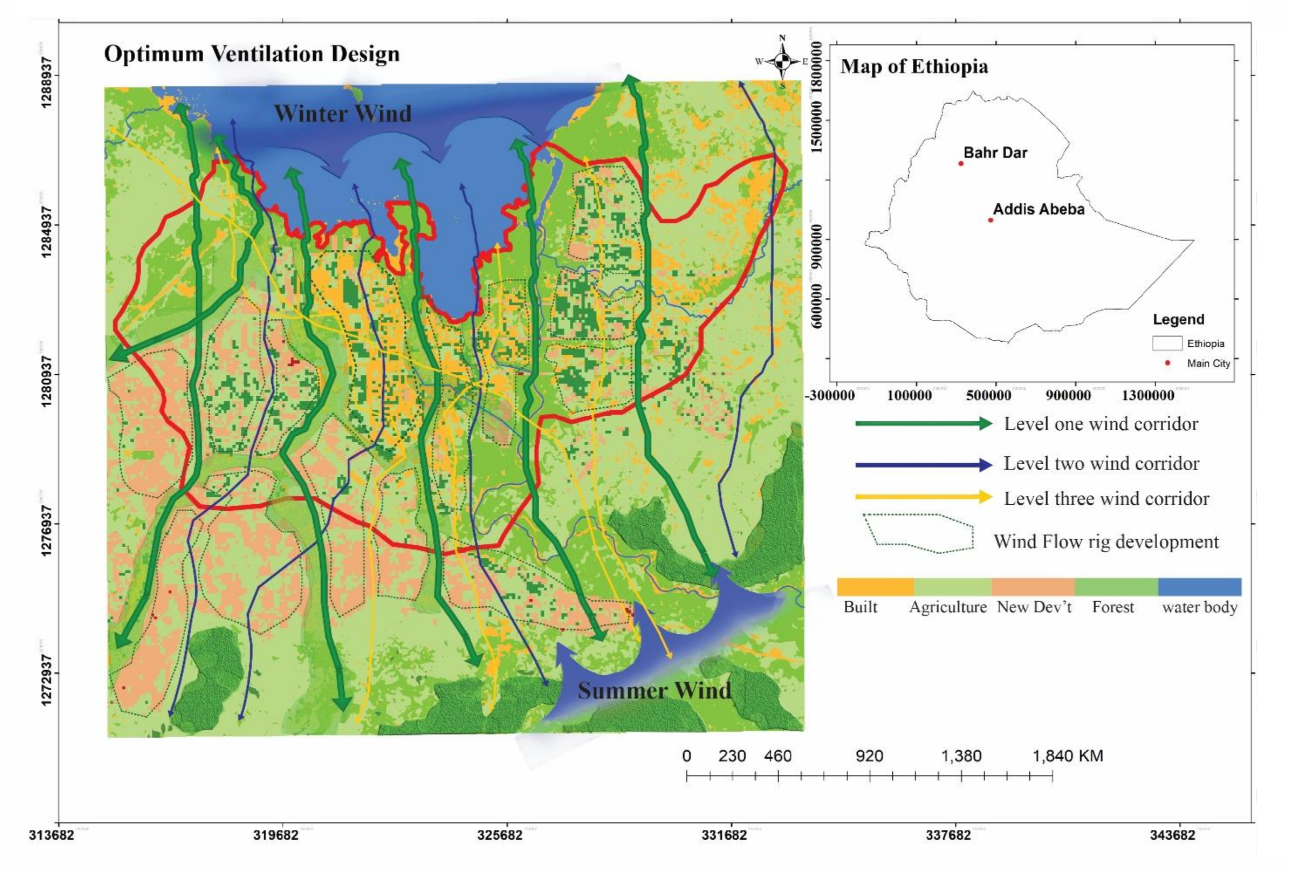


Figure 25: Optimum ventilation corridor design

## Estimating maximum density using ventilation corridor design by CFD

The building shape is designed for maximum obstruction of wind flow and SVF shadow with a maximum size of 20m x 30m building. City center ventilation have been tested by CFD ANSYS simulation. Figure 26 shows the city center ventilation performance that is designed 50% built density. The simulation shows the ventilation between buildings is relatively high. The simulation design on the dry season wind with speed of source 3.5m/s of reference wind. The northern side of the city have get very high ventilation breeze from Lake Tana. The building height from the lake side have started from the existing building height of G+ 7 to allow the wind into city center with low obstruction.

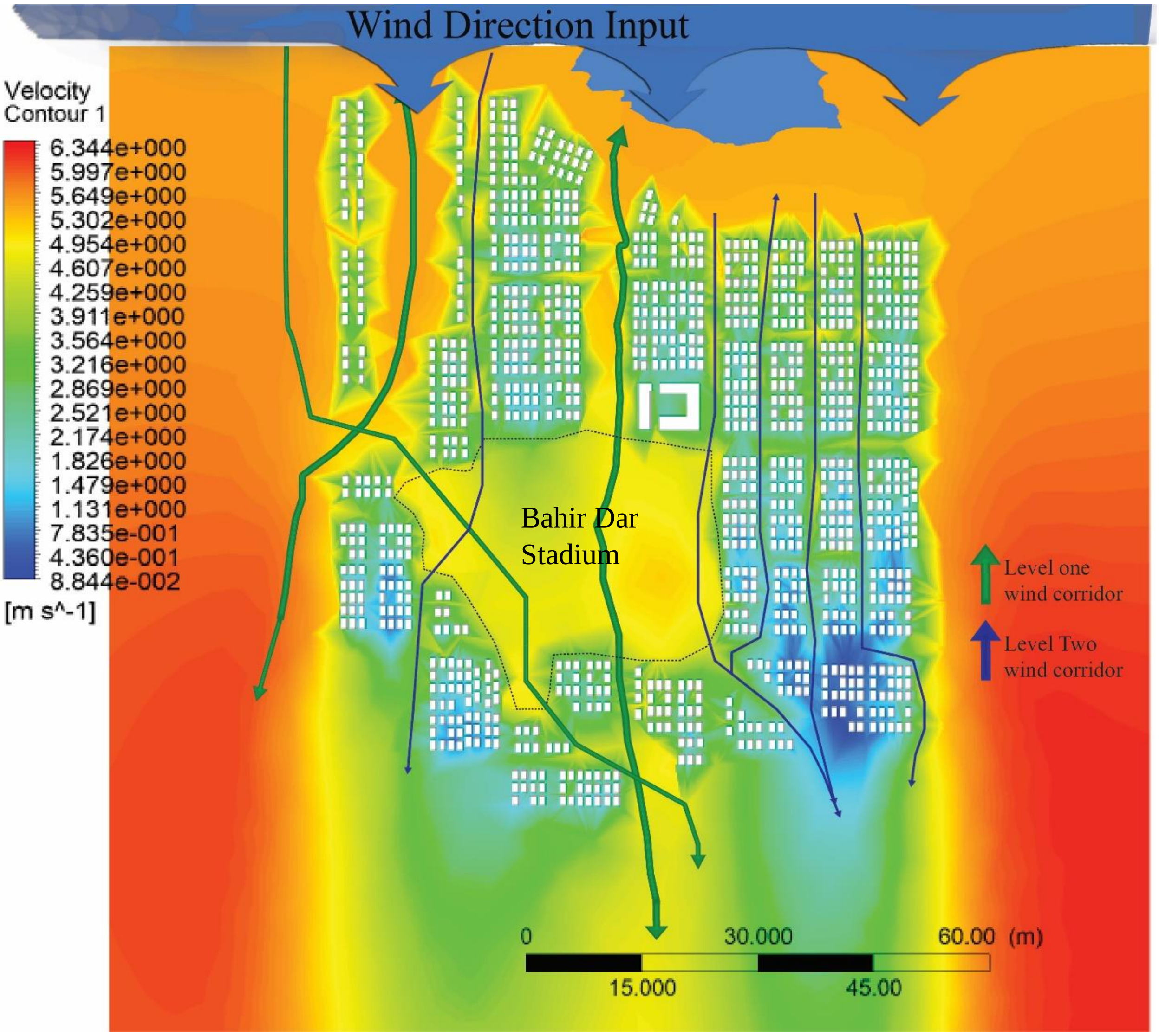


Figure 26: Optimum density at 20m height

Figure 27 shows the ventilation performance at 35m height. The ventilation performance increased and the roughness length decreased to 0.3 and the southern part of the city get high ventilation performance. The ventilation potential index 0.8 have been increased to 0.7 as the roughness of building decreased and sky view factor increased as the base point height increase from ground to 35m height.

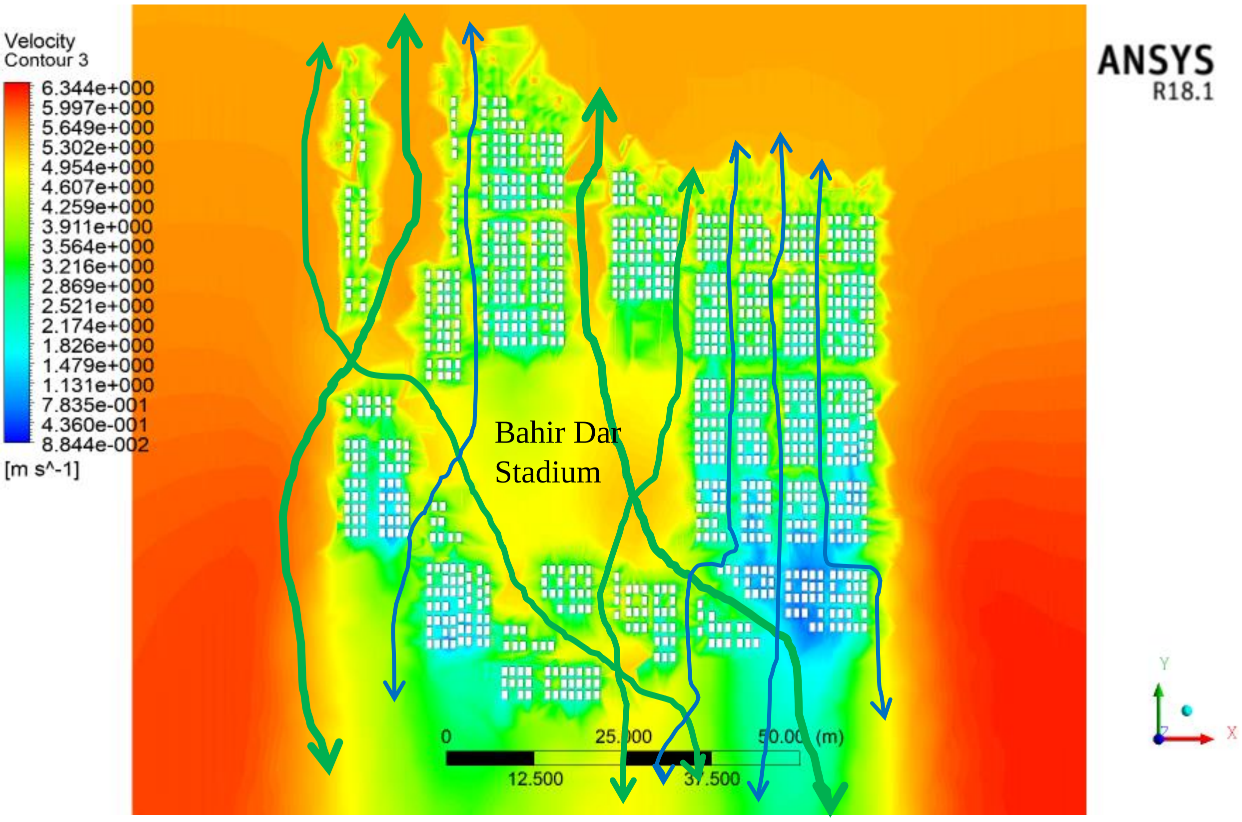


Figure 27: Optimum density at 35m height

Figure 28 shows the sectional view of building height sky line view of the final design. The sky line base starts from 12m height buildings of the existing building height. The ventilation between buildings is very good.

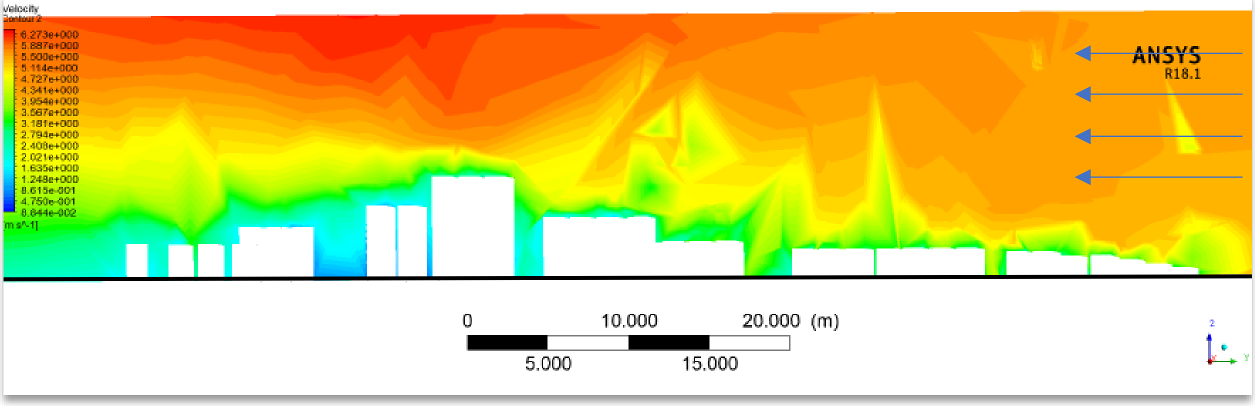


Figure 28: Sectional view of wind Pattern

# CHAPTER FIVE

# SUMMERY OF FINDINGS

## 5.1 Ventilation Potential of Bahir Dar

### i. Roughness Length of Existing Land Use Land Cover

The roughness length (RL) of existing land use land cover of Bahir Dar city is done by remote sensing and GIS multiple criteria, and also CFD software. Meteorological data and land use type to calculate the RL, and the morphological method, which uses the geometric shape of the roughness element and its distribution density to calculate the RL (Liu *et al.*, 2016). The RL of Bahir Dar studied without built environment and current built environment. The RL before built is low and after built is relatively high. The RL of terrain is from 0.009 to 1 of minimum and maximum respectively, and also built environment RL is 0.032 to 1 of minimum and maximum respectively. The current RL of Bahir Dar is slightly high.

### ii. Sky View Factor (SVF) Calculation

The SVF is a numerical value describing the 3D urban form, and it reflects the different geometrical forms of urban street channels (Liu *et al.*, 2016). SAGA GIS, Orbit GIS, SVF calculator and other methodology's. For this study SAGA GIS is used to calculate the SVF of Bahir Dar. The SVF of Bahir Dar city with surrounding area are 0.13 to 1.5 from lowest to highest view.

## 5.2 Estimating the Ventilation Potential of Bahir Dar

This study tested the existing wind flow gap and urban planning morphology arrangement; according to the prevailing wind. The existing wind pattern ventilation performance test helps to identify the gap of density in the city. The study results from the major central business district and market places have got low ventilation performance. To get fresh air with the optimum density design needs consideration of prevailing wind flow *(He*, Ding, and Prasad, 2019). The ventilation before construction are relatively high. At the exiting built environment at dry season the southern part of the city have low ventilation potential. The existing built environment ventilation potential index result is 0.5 at ground level land cover.

## 5.3 Estimating the Ventilation Potential of New Master Plan of Bahir Dar

Bahir Dar city has prepared a new structural plan with medium and high-density development of the city. The study test this future Bahir Dar development type. The structure plan has keep major street already developed and change of density as well as building height. The ventilation potential estimated by using master plan land use as a land cover surface roughness and sky view factor. The study uses multiple suitability criteria of ventilation performance to estimate ventilation potential index. The southern part of the city ventilation slightly low. The ventilation potential index is 0.4 of new master plan proposal. Generally the new master plan proposal low ventilation performance.

## 5.4 Optimum Ventilation Design

The results are directly related to the criteria used for design of ventilation corridor and optimum density. According to the criteria use in table 8, from the criteria used for design ventilation corridor (40 %) land use, (10 %) terrain roughness, (30%) sky view factor and (20%) ventilation corridor buffer. According to Ren *et al.* (2018), land use and sky view factor have given high priority for design ventilation corridor. From the land use water body, ponds, river and open space have given high grade for ventilation corridor design.

The final result of this study shows 0.5 ventilation potential index by decreasing roughness to 0.4 and optimum density of built environment 50%. This shows all city part can cool from Lake Tana breeze. The result shows this method is effective for city ventilation assessment.

# CHAPTER SIX

# CONCLUSION AND RECOMMENDATION

## 6.1. Conclusion

Designing the city by considering passive cooling system is the main mechanism of reducing usage of high energy for cooling. The study explored investigating the paradoxes of density and Lake Tana's Breeze of Bahir Dar city based on remote sensing (RS) and GIS technology. The presented study mainly deals ventilation potential of city based on prevailing wind on hot climate parameter.

The main ventilation source of Bahir Dar city have been studied from regional level to block level. The aim is to decide the density and source of natural ventilation for Bahir Dar city. The major ventilation corridor; Lake Tana, River Abay, Chockie Mountain at regional level as well as at city level. At high temperature season from February to May the fresh air flows from North to South. The analysis shows that the maximum prevailing wind flows from North to South direction and the monsoon wind that flows from South west to North East.

The existing ventilation potential analysis shows the ventilation potential index is slightly high needs some intervention of buffer design. The ventilation performance of new structure plan proposal is relatively low and due to high density built up area.

This study results investigating the ventilation potential of the existing density and land use proposal with ventilation potential index of 0.5 and design urban ventilation corridor with using GIS and remote (RS) of ventilation potential index of 0.4 and design the city based on the ventilation corridor design of 50% optimum density.

## 6.2. Recommendation

Design and implementation of urban ventilation corridor design mainly related to master plan preparation proposal issues for sustainable city design. This study indicates how to design ventilation corridor in cities hot climate region. The ventilation corridor is not only as a ventilation but also used as public space.

Ethiopian city development agency must revises the planning approach according to the city location and micro climate data. Climate category of Ethiopian city and design standard preparation manual is needed. This study gives a relevant information on how the design is changed from the physical planning philosophy to climate responsive approach.

Bahir Dar city Administration must consider the potential of Lake Tana city breeze and energy consumption for cooling, and revise the master plan based on high ventilation performance of Bahir Dar.

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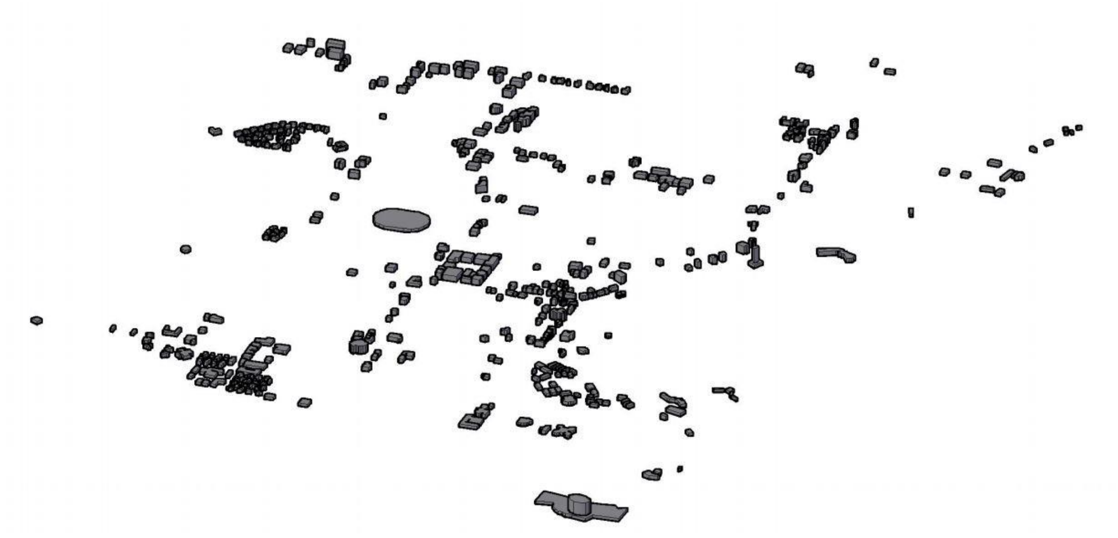
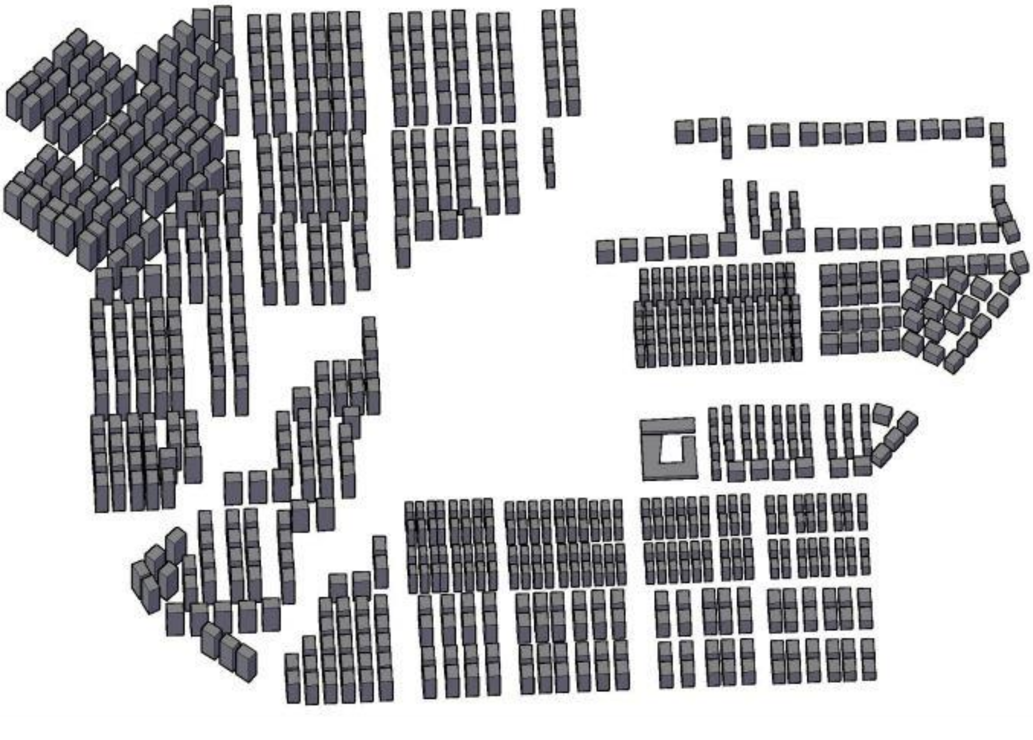
# Annex

**Annex 1:** 3D model of Existing high raise building of Bahir Dar



Annex 2: 3D model of Optimum Density of Bahir Dar



Annex 3: Land sat 8 landuse land cover 2020 text.t

```
Direction,      Calm, 2.0  4.9, 5.0  6.9, 7.0  9.9,10.0 14.9,15.0 19.9,
20.0+
355-004  ,     34.61,     9.724,     2.842,     1.363,     0.838,     0.071,
0.024
005-014  ,          ,     0.285,     0.121,     0.066,     0.037,     0.008,
0.016
015-024  ,          ,     0.751,     0.340,     0.171,     0.153,     0.008,
0.011
025-034  ,          ,     1.566,     0.290,     0.098,     0.069,     0.018,
0.003
035-044  ,          ,     0.398,     0.071,     0.029,     0.024,     0.008,
0.003
045-054  ,          ,     0.551,     0.266,     0.090,     0.045,     0.016,
0.005
055-064  ,          ,     1.825,     0.211,     0.098,     0.042,     0.011,
0.000
065-074  ,          ,     0.435,     0.069,     0.034,     0.029,     0.003,
0.003
075-084  ,          ,     0.425,     0.084,     0.026,     0.024,     0.003,
0.003
085-094  ,          ,     2.958,     0.630,     0.229,     0.185,     0.024,
0.011
095-104  ,          ,     0.303,     0.084,     0.034,     0.034,     0.005,
0.008
105-114  ,          ,     0.206,     0.032,     0.016,     0.011,     0.000,
0.003
115-124  ,          ,     1.274,     0.224,     0.098,     0.074,     0.008,
0.008
125-134  ,          ,     0.216,     0.066,     0.016,     0.013,     0.005,
0.005
135-144  ,          ,     0.593,     0.195,     0.069,     0.069,     0.008,
0.005
145-154  ,          ,     0.841,     0.258,     0.079,     0.069,     0.003,
0.003
155-164  ,          ,     1.624,     0.374,     0.100,     0.053,     0.003,
0.003
165-174  ,          ,     1.332,     0.256,     0.042,     0.037,     0.003,
0.003
175-184  ,          ,     7.612,     0.899,     0.195,     0.071,     0.029,
0.013
185-194  ,          ,     0.425,     0.121,     0.021,     0.026,     0.003,
0.005
195-204  ,          ,     0.475,     0.045,     0.005,     0.013,     0.008,
0.003
205-214  ,          ,     0.675,     0.132,     0.024,     0.013,     0.000,
0.000
215-224  ,          ,     0.274,     0.053,     0.021,     0.005,     0.008,
0.000
225-234  ,          ,     0.319,     0.121,     0.058,     0.026,     0.003,
0.013
235-244  ,          ,     0.686,     0.082,     0.026,     0.037,     0.008,
0.005
245-254  ,          ,     0.340,     0.090,     0.055,     0.026,     0.005,
0.003
255-264  ,          ,     0.567,     0.124,     0.050,     0.021,     0.005,
0.000
265-274  ,          ,     2.442,     0.485,     0.190,     0.076,     0.013,
0.018
```

```
275-284  ,          ,    0.435,    0.124,    0.055,    0.034,    0.008,
0.008
285-294  ,          ,    0.332,    0.127,    0.066,    0.029,    0.003,
0.005
295-304  ,          ,    0.899,    0.132,    0.055,    0.042,    0.005,
0.000
305-314  ,          ,    0.190,    0.079,    0.032,    0.029,    0.005,
0.003
315-324  ,          ,    0.823,    0.187,    0.119,    0.055,    0.003,
0.003
325-334  ,          ,    0.983,    0.351,    0.198,    0.111,    0.016,
0.013
335-344  ,          ,    1.384,    0.430,    0.285,    0.250,    0.029,
0.018
345-354  ,          ,    1.751,    0.860,    0.662,    0.501,    0.069,
0.021
```

## Annex 4: Meteorological climate data of Bahir Dar

-BEGIN HEADER-
NASA/POWER SRB/FLASHFlux/MERRA2/GEOS 5.12.4 (FP-IT) 0.5 x 0.5 Degree Interannual Averages/Sums
Dates (month/day/year): 01/01/2000 through 12/31/2018
Location: Latitude 11.5966 Longitude 37.3843
Elevation from MERRA-2: Average for 1/2x1/2 degree lat/lon region = 1910.41 meters Site = na
Climate zone: na (reference Briggs et al: http://www.energycodes.gov)
Value for missing model data cannot be computed or out of model availability range: -999
Before January 2018 the precipitation is reported as an accumulation After it is in average rate.
Parameter(s):
WS50M_MIN MERRA2 1/2x1/2 Minimum Wind Speed at 50 Meters (m/s)
RH2M MERRA2 1/2x1/2 Relative Humidity at 2 Meters (%)
WS10M_MIN MERRA2 1/2x1/2 Minimum Wind Speed at 10 Meters (m/s)
WS50M MERRA2 1/2x1/2 Wind Speed at 50 Meters (m/s)
T2M_MAX MERRA2 1/2x1/2 Maximum Temperature at 2 Meters (C)
WS50M_MAX MERRA2 1/2x1/2 Maximum Wind Speed at 50 Meters (m/s)
QV2M MERRA2 1/2x1/2 Specific Humidity at 2 Meters (g/kg)
T2M_MIN MERRA2 1/2x1/2 Minimum Temperature at 2 Meters (C)
PRECTOT MERRA2 1/2x1/2 Precipitation (mm day-1)
WS10M MERRA2 1/2x1/2 Wind Speed at 10 Meters (m/s)
WS10M_MAX MERRA2 1/2x1/2 Maximum Wind Speed at 10 Meters (m/s)
-END HEADER-

| LAT | LON | PARAMETER | YEAR | JAN |  | FEB | MAR | APR | MAY | JUN |  | JUL | AUG | SEP | OCT | NOV | DEC | ANN |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 11.59661 | 37.38431 | PRECTOT | 2000 | 0.13 | 0.28 | 10.05 | 51.18 | 108.6 | 261.2 | 378.9 | 317.7 | 187.3 | 113.68 | 14.48 | 4.92 | 1448.3 |  |  |
| 11.59661 | 37.38431 | PRECTOT | 2001 | 0.68 | 5.44 | 25.69 | 66.45 | 127.1 | 159.8 | 230.7 | 290.6 | 147.9 | 104.58 | 12.05 | 5.63 | 1176.5 |  |  |
| 11.59661 | 37.38431 | PRECTOT | 2002 | 6.88 | 3.18 | 60.8 | 42.75 | 33.33 | 205.6 | 297.2 | 265.6 | 117.9 | 29.5 | 6.89 | 3.43 | 1073 |  |  |
| 11.59661 | 37.38431 | PRECTOT | 2003 | 0.35 | 12.27 | 22.72 | 6.86 | 29.27 | 152.5 | 307.4 | 327.2 | 181.3 | 15.89 | 8.7 | 25.9 | 1090.3 |  |  |
| 11.59661 | 37.38431 | PRECTOT | 2004 | 1.1 | 3.2 | 5.19 | 88.05 | 52.41 | 154.3 | 296.1 | 194.2 | 163.2 | 45.88 | 23.21 | 9.4 | 1036.2 |  |  |
| 11.59661 | 37.38431 | PRECTOT | 2005 | 5.15 | 1.21 | 24.51 | 55.33 | 132.6 | 161.6 | 365.2 | 278.8 | 162.2 | 34.32 | 7.53 | 0 | 1228.3 |  |  |
| 11.59661 | 37.38431 | PRECTOT | 2006 | 1.26 | 7.52 | 41.99 | 45.85 | 190.1 | 311.3 | 618.9 | 413.6 | 305.3 | 193.31 | 34.98 | 11.4 | 2175.3 |  |  |
| 11.59661 | 37.38431 | PRECTOT | 2007 | 8.67 | 10.57 | 30.82 | 72.34 | 185.9 | 228.6 | 496.8 | 402.3 | 184.8 | 68.19 | 8.27 | 0.21 | 1697.4 |  |  |
| 11.59661 | 37.38431 | PRECTOT | 2008 | 6.17 | 0.05 | 1.76 | 69.81 | 155.3 | 210.7 | 420.6 | 475.4 | 190 | 78.48 | 45.06 | 2.74 | 1656 |  |  |
| 11.59661 | 37.38431 | PRECTOT | 2009 | 11.87 | 11.45 | 21.39 | 49.76 | 29.84 | 162.2 | 464.7 | 371.8 | 173 | 115.22 | 9.57 | 9.38 | 1430.2 |  |  |
| 11.59661 | 37.38431 | PRECTOT | 2010 | 1.69 | 0.88 | 24.27 | 70.94 | 178.8 | 226.8 | 396.6 | 439.5 | 240.3 | 26.62 | 15.85 | 2.52 | 1624.7 |  |  |
| 11.59661 | 37.38431 | PRECTOT | 2011 | 8.73 | 0.21 | 28.52 | 25.25 | 183.5 | 204.1 | 232.4 | 202.6 | 145.6 | 14.63 | 49.38 | 0.18 | 1095.2 |  |  |
| 11.59661 | 37.38431 | PRECTOT | 2012 | 0.05 | 0 | 13.67 | 13.72 | 82.28 | 136.2 | 425.3 | 404.3 | 213.7 | 38.01 | 56.6 | 12.5 | 1396.4 |  |  |
| 11.59661 | 37.38431 | PRECTOT | 2013 | 1.54 | 0.5 | 12.45 | 27.84 | 239.6 | 258 | 525.5 | 444.6 | 206.4 | 164.07 | 35.1 | 0.19 | 1915.7 |  |  |
| 11.59661 | 37.38431 | PRECTOT | 2014 | 2.31 | 5.23 | 50.12 | 86.48 | 219.9 | 227.6 | 574 | 440.1 | 369.7 | 167.3 | 14.95 | 14 | 2171.6 |  |  |
| 11.59661 | 37.38431 | PRECTOT | 2015 | 1.85 | 4.76 | 26.52 | 2.29 | 107.9 | 253 | 249 | 460.2 | 168.1 | 82.51 | 52.06 | 44.1 | 1452.2 |  |  |
| 11.59661 | 37.38431 | PRECTOT | 2016 | 2.46 | 2.24 | 36.94 | 37.45 | 239.3 | 209.8 | 534.8 | 444.7 | 168 | 43.54 | 1.68 | 0.19 | 1721 |  |  |
| 11.59661 | 37.38431 | PRECTOT | 2017 | 0.06 | 35.63 | 30.81 | 104.4 | 207.5 | 154.3 | 441.9 | 388.2 | 220.2 | 38.67 | 8.57 | 0.37 | 1630.6 |  |  |
| 11.59661 | 37.38431 | PRECTOT | 2018 | 0.03 | 0.76 | 0.21 | 1.64 | 2.34 | 5.88 | 11.32 | 10.16 | 3.85 | 2.76 | 1.99 | 0.14 | 3.45 |  |  |
| 11.59661 | 37.38431 | RH2M | 2000 | 49.13 | 41.13 | 38.29 | 46.96 | 51.96 | 69.36 | 84.3 | 85.97 | 77.93 | 73.14 | 61.2 | 55.7 | 61.33 |  |  |
| 11.59661 | 37.38431 | RH2M | 2001 | 46.21 | 42.3 | 36.02 | 44.82 | 50.75 | 68.09 | 81.01 | 86.25 | 73.88 | 67.24 | 54.8 | 52.1 | 58.73 |  |  |
| 11.59661 | 37.38431 | RH2M | 2002 | 48.73 | 37.8 | 42.32 | 41.17 | 33.29 | 63.96 | 74.14 | 79.28 | 71.14 | 58.36 | 51.61 | 46.5 | 54.12 |  |  |
| 11.59661 | 37.38431 | RH2M | 2003 | 36.38 | 37.34 | 38.24 | 29.9 | 32.36 | 63.43 | 82.6 | 85.3 | 76.71 | 58.04 | 51.89 | 45.8 | 53.27 |  |  |
| 11.59661 | 37.38431 | RH2M | 2004 | 41.12 | 37.25 | 30.19 | 45.7 | 42.1 | 65.16 | 78.66 | 81.86 | 73.46 | 60.29 | 53.38 | 49.3 | 54.92 |  |  |
| 11.59661 | 37.38431 | RH2M | 2005 | 41.16 | 31.65 | 37.52 | 35.54 | 45.18 | 69.29 | 84.29 | 83.98 | 78.52 | 64.07 | 52.85 | 39 | 55.41 |  |  |
| 11.59661 | 37.38431 | RH2M | 2006 | 37.99 | 34.77 | 35.98 | 41.96 | 57.25 | 68.09 | 82.66 | 86.23 | 75.85 | 66.23 | 63 | 60.2 | 59.35 |  |  |
| 11.59661 | 37.38431 | RH2M | 2007 | 52.48 | 42.42 | 37.32 | 43.81 | 53.47 | 74.19 | 85.74 | 85.17 | 78.24 | 60.31 | 54.46 | 41.4 | 59.18 |  |  |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 11.59661 | 37.38431 | RH2M | 2008 | 46.64 | 34.87 | 25.18 | 45.83 | 55.66 | 70.44 | 82.37 | 83.19 | 75.74 | 66.42 | 55.8 | 49.8 | 57.74 |
| 11.59661 | 37.38431 | RH2M | 2009 | 41.77 | 39.43 | 38.83 | 39.45 | 36.89 | 63.04 | 83.3 | 82.73 | 70.43 | 63.68 | 54.18 | 52.5 | 55.64 |
| 11.59661 | 37.38431 | RH2M | 2010 | 43.78 | 35.76 | 37.03 | 45.9 | 59.8 | 72.01 | 84.79 | 87.6 | 78.08 | 63.38 | 56.67 | 50.9 | 59.8 |
| 11.59661 | 37.38431 | RH2M | 2011 | 47.86 | 31.54 | 38.8 | 36.41 | 54.64 | 71.97 | 80.62 | 83.09 | 76.38 | 59.14 | 60.01 | 46.5 | 57.42 |
| 11.59661 | 37.38431 | RH2M | 2012 | 41.84 | 28.12 | 31.77 | 29.51 | 48.92 | 64.27 | 84.43 | 86.67 | 78.74 | 61.76 | 62.99 | 53.9 | 56.2 |
| 11.59661 | 37.38431 | RH2M | 2013 | 45.1 | 34.5 | 32.92 | 33.07 | 57.73 | 72.57 | 85.46 | 87.09 | 75.98 | 68.79 | 63.89 | 51 | 59.19 |
| 11.59661 | 37.38431 | RH2M | 2014 | 46.83 | 39.27 | 47.04 | 47.95 | 65.45 | 68.62 | 83.57 | 86.11 | 79.26 | 71.38 | 63.52 | 54.8 | 62.99 |
| 11.59661 | 37.38431 | RH2M | 2015 | 48.58 | 34.98 | 36.33 | 33.79 | 55.56 | 66.74 | 76.76 | 83.15 | 74.86 | 66.88 | 65.54 | 67.3 | 59.39 |
| 11.59661 | 37.38431 | RH2M | 2016 | 52.33 | 40.9 | 39.06 | 36.98 | 67.13 | 71.17 | 86 | 85.84 | 76.63 | 65.72 | 50.54 | 43.8 | 59.78 |
| 11.59661 | 37.38431 | RH2M | 2017 | 30.77 | 48.21 | 39.81 | 45.22 | 64.69 | 69.43 | 82.88 | 86.73 | 78.48 | 69.1 | 59.21 | 43.8 | 59.92 |
| 11.59661 | 37.38431 | RH2M | 2018 | 44.2 | 38.46 | 33 | 39.77 | 49.94 | 71.73 | 83.96 | 85.21 | 72.82 | 68.59 | 62.25 | 56.5 | 59.01 |
| 11.59661 | 37.38431 | T2M_MAX | 2000 | 26.08 | 28.6 | 30.55 | 27.93 | 29.09 | 25.11 | 20.81 | 20.78 | 22.55 | 23.12 | 24.13 | 24.8 | 25.28 |
| 11.59661 | 37.38431 | T2M_MAX | 2001 | 26.29 | 28.64 | 29.36 | 29.84 | 28.67 | 24.31 | 21.31 | 20.98 | 23.32 | 24.06 | 24.36 | 26 | 25.57 |
| 11.59661 | 37.38431 | T2M_MAX | 2002 | 26.85 | 29.47 | 28.99 | 30.06 | 30.94 | 26.03 | 24.02 | 22.31 | 23.62 | 25.09 | 26.2 | 27 | 26.7 |
| 11.59661 | 37.38431 | T2M_MAX | 2003 | 28.43 | 29.79 | 30.08 | 31.31 | 31.89 | 26.18 | 21.22 | 21.33 | 23.21 | 24.84 | 25.76 | 26.5 | 26.69 |
| 11.59661 | 37.38431 | T2M_MAX | 2004 | 28.25 | 29.59 | 30.86 | 28.66 | 30.92 | 25.48 | 22.25 | 21.89 | 23.72 | 24.48 | 25.84 | 26.9 | 26.56 |
| 11.59661 | 37.38431 | T2M_MAX | 2005 | 27.35 | 31.03 | 30.29 | 30.84 | 28.79 | 25.59 | 20.67 | 21.61 | 22.83 | 24.06 | 25.21 | 26.6 | 26.2 |
| 11.59661 | 37.38431 | T2M_MAX | 2006 | 28.59 | 30.09 | 29.56 | 29.3 | 27.71 | 24.96 | 21.53 | 20.81 | 22.73 | 23.76 | 23.54 | 24.4 | 25.55 |
| 11.59661 | 37.38431 | T2M_MAX | 2007 | 25.86 | 28.21 | 30.47 | 29.6 | 28.43 | 23.78 | 20.64 | 21.03 | 22.63 | 23.58 | 24.43 | 25.8 | 25.35 |
| 11.59661 | 37.38431 | T2M_MAX | 2008 | 27.21 | 29.11 | 31.16 | 28.53 | 27.6 | 24.55 | 21.53 | 21.55 | 22.9 | 23.54 | 23.76 | 25.1 | 25.53 |
| 11.59661 | 37.38431 | T2M_MAX | 2009 | 26.88 | 28.83 | 29.69 | 30.32 | 30.97 | 27.25 | 21.18 | 22.12 | 23.75 | 23.66 | 24.41 | 25.3 | 26.17 |
| 11.59661 | 37.38431 | T2M_MAX | 2010 | 26.98 | 29.19 | 29.58 | 29.32 | 27.22 | 24.83 | 20.91 | 20.5 | 22.69 | 23.99 | 24.12 | 24.8 | 25.31 |
| 11.59661 | 37.38431 | T2M_MAX | 2011 | 26.27 | 29.62 | 28.78 | 30.72 | 27.64 | 24.22 | 21.6 | 21.64 | 22.83 | 24.74 | 24.43 | 26.3 | 25.7 |
| 11.59661 | 37.38431 | T2M_MAX | 2012 | 27.88 | 30.26 | 30.55 | 30.52 | 29.29 | 26.15 | 21.12 | 20.94 | 22.63 | 24.06 | 24.06 | 25.3 | 26.04 |
| 11.59661 | 37.38431 | T2M_MAX | 2013 | 27.2 | 29.71 | 30.31 | 30.43 | 27.32 | 23.95 | 20.34 | 20.4 | 23.17 | 23.16 | 23.94 | 24.4 | 25.32 |
| 11.59661 | 37.38431 | T2M_MAX | 2014 | 26.33 | 28.27 | 28.48 | 28.78 | 25.79 | 25.28 | 21.77 | 20.91 | 22.33 | 22.98 | 23.5 | 24.1 | 24.85 |
| 11.59661 | 37.38431 | T2M_MAX | 2015 | 25.93 | 28.97 | 30.31 | 31.13 | 27.96 | 25.75 | 23.39 | 22.18 | 23.74 | 24.79 | 24.64 | 24.5 | 26.08 |
| 11.59661 | 37.38431 | T2M_MAX | 2016 | 26.02 | 29.15 | 30.8 | 30.01 | 25.66 | 25.4 | 20.86 | 20.82 | 23.03 | 24.01 | 24.91 | 26 | 25.53 |
| 11.59661 | 37.38431 | T2M_MAX | 2017 | 27.72 | 27.46 | 29.14 | 29.61 | 26.23 | 26.17 | 22.41 | 21.24 | 23.12 | 24.11 | 24.81 | 25.7 | 25.63 |
| 11.59661 | 37.38431 | T2M_MAX | 2018 | 26.52 | 28.77 | 29.74 | 28.86 | 29.22 | 24.56 | 21.31 | 21.03 | 23.71 | 23.92 | 24.34 | 25.7 | 25.62 |
| 11.59661 | 37.38431 | T2M_MIN | 2000 | 13.24 | 15.16 | 17.37 | 17.2 | 17.78 | 16.41 | 14.95 | 15.08 | 15.72 | 15.49 | 13.4 | 13.5 | 15.44 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 11.59661 | 37.38431 | T2M_MIN | 2001 | 12.92 | 15.77 | 16.65 | 17.97 | 18.27 | 16.28 | 15.34 | 15.29 | 15.9 | 15.25 | 12.85 | 14.2 | 15.55 |
| 11.59661 | 37.38431 | T2M_MIN | 2002 | 13.73 | 16.21 | 17.22 | 17.7 | 18.79 | 17.13 | 16.42 | 15.72 | 15.95 | 14.48 | 14.83 | 14.2 | 16.02 |
| 11.59661 | 37.38431 | T2M_MIN | 2003 | 13.93 | 16.42 | 17.53 | 18.44 | 19.79 | 17.13 | 15.39 | 15.5 | 16.22 | 14.24 | 13.82 | 12.7 | 15.92 |
| 11.59661 | 37.38431 | T2M_MIN | 2004 | 14.19 | 15.32 | 17.18 | 17.66 | 17.98 | 16.52 | 15.32 | 15.53 | 16.15 | 14.14 | 14.37 | 14.2 | 15.71 |
| 11.59661 | 37.38431 | T2M_MIN | 2005 | 12.71 | 16.39 | 17.54 | 18.86 | 17.71 | 16.95 | 15.11 | 15.69 | 16.15 | 14.83 | 13.58 | 12 | 15.61 |
| 11.59661 | 37.38431 | T2M_MIN | 2006 | 14.11 | 16.06 | 16.47 | 17.51 | 17.74 | 16.67 | 15.66 | 15.48 | 15.93 | 14.59 | 13.13 | 13.3 | 15.55 |
| 11.59661 | 37.38431 | T2M_MIN | 2007 | 13.37 | 14.91 | 17.12 | 17.63 | 18.04 | 16.41 | 15.32 | 15.46 | 15.96 | 13.61 | 12.49 | 11.3 | 15.13 |
| 11.59661 | 37.38431 | T2M_MIN | 2008 | 13.99 | 14.64 | 16.48 | 17.08 | 17.48 | 16.33 | 15.42 | 15.66 | 15.94 | 14.57 | 12.96 | 13.2 | 15.31 |
| 11.59661 | 37.38431 | T2M_MIN | 2009 | 13.27 | 16.44 | 17.78 | 17.77 | 18.22 | 17.21 | 15.29 | 16.11 | 16.06 | 14.69 | 13.22 | 13.9 | 15.82 |
| 11.59661 | 37.38431 | T2M_MIN | 2010 | 14.3 | 15.86 | 16.64 | 18.81 | 18.31 | 16.92 | 15.53 | 15.55 | 16 | 14.7 | 14.04 | 13.5 | 15.84 |
| 11.59661 | 37.38431 | T2M_MIN | 2011 | 13.59 | 14.6 | 16.22 | 18.66 | 17.98 | 16.69 | 15.49 | 15.47 | 15.71 | 14.17 | 13.81 | 13 | 15.44 |
| 11.59661 | 37.38431 | T2M_MIN | 2012 | 13.8 | 14.38 | 16.81 | 17.71 | 17.92 | 16.71 | 15.34 | 15.67 | 16.12 | 14.41 | 14.93 | 13.2 | 15.58 |
| 11.59661 | 37.38431 | T2M_MIN | 2013 | 14.33 | 15.61 | 17.96 | 17.89 | 17.85 | 16.37 | 14.91 | 15.14 | 16.12 | 14.91 | 14.12 | 12.1 | 15.61 |
| 11.59661 | 37.38431 | T2M_MIN | 2014 | 13.74 | 14.54 | 16.92 | 17.81 | 17.67 | 16.91 | 15.76 | 15.51 | 15.73 | 14.74 | 13.47 | 12.6 | 15.45 |
| 11.59661 | 37.38431 | T2M_MIN | 2015 | 12.63 | 15.14 | 17.37 | 18.59 | 17.96 | 17.05 | 16.48 | 16.07 | 16.48 | 15.46 | 14.48 | 14.1 | 15.98 |
| 11.59661 | 37.38431 | T2M_MIN | 2016 | 13.42 | 15.75 | 18.48 | 18.53 | 17.48 | 16.94 | 15.5 | 15.34 | 16.04 | 14.9 | 12.53 | 12 | 15.57 |
| 11.59661 | 37.38431 | T2M_MIN | 2017 | 11.55 | 15.49 | 16.69 | 18.13 | 17.91 | 17.19 | 16.09 | 15.67 | 16.27 | 15.58 | 13.9 | 12.3 | 15.56 |
| 11.59661 | 37.38431 | T2M_MIN | 2018 | 12.64 | 15.52 | 16.38 | 17.51 | 18.04 | 16.43 | 15.47 | 15.21 | 15.83 | 15.13 | 14.12 | 13.9 | 15.51 |
| 11.59661 | 37.38431 | WS50M_MIN | 2000 | 1.05 | 0.79 | 1.06 | 1.89 | 0.95 | 1.34 | 1.79 | 1.56 | 1.41 | 1.1 | 1.13 | 0.83 | 1.24 |
| 11.59661 | 37.38431 | WS50M_MIN | 2001 | 1.03 | 0.96 | 1.03 | 1.83 | 1.11 | 1.57 | 1.73 | 2.03 | 1.29 | 1.9 | 1.31 | 0.99 | 1.4 |
| 11.59661 | 37.38431 | WS50M_MIN | 2002 | 0.99 | 1.17 | 0.91 | 1.8 | 1.08 | 1.53 | 1.24 | 1.2 | 1.59 | 2.02 | 1.34 | 1.14 | 1.33 |
| 11.59661 | 37.38431 | WS50M_MIN | 2003 | 1.04 | 1.04 | 0.88 | 1.61 | 1.56 | 1.5 | 2.04 | 2.27 | 1.22 | 1.89 | 1.2 | 1.39 | 1.47 |
| 11.59661 | 37.38431 | WS50M_MIN | 2004 | 1.12 | 1.12 | 1.02 | 1.66 | 1.89 | 1.04 | 1.14 | 1.34 | 1.76 | 1.83 | 1.31 | 0.83 | 1.34 |
| 11.59661 | 37.38431 | WS50M_MIN | 2005 | 1.63 | 1.18 | 1.19 | 1.23 | 1.27 | 1.38 | 1.78 | 1.37 | 1.56 | 1.84 | 1.29 | 0.8 | 1.38 |
| 11.59661 | 37.38431 | WS50M_MIN | 2006 | 1.45 | 1.14 | 1.12 | 0.87 | 1.63 | 1.22 | 1.45 | 1.56 | 1.08 | 1.86 | 1.33 | 1.16 | 1.33 |
| 11.59661 | 37.38431 | WS50M_MIN | 2007 | 1.11 | 1.1 | 1.28 | 1.23 | 1.77 | 1.27 | 2.25 | 1.37 | 1.44 | 2.1 | 1.66 | 1.57 | 1.52 |
| 11.59661 | 37.38431 | WS50M_MIN | 2008 | 1.16 | 1.65 | 1.55 | 1.69 | 1.49 | 1.52 | 1.34 | 1.03 | 1.24 | 1.98 | 1.2 | 0.81 | 1.39 |
| 11.59661 | 37.38431 | WS50M_MIN | 2009 | 0.89 | 0.86 | 1.19 | 1.75 | 2.15 | 1.17 | 1.43 | 1.45 | 1.34 | 2.32 | 1.31 | 1.01 | 1.41 |
| 11.59661 | 37.38431 | WS50M_MIN | 2010 | 0.85 | 1.49 | 1.22 | 1.15 | 1.13 | 1.15 | 1.95 | 1.61 | 1.35 | 2.29 | 1.06 | 1.07 | 1.36 |
| 11.59661 | 37.38431 | WS50M_MIN | 2011 | 1.16 | 1.62 | 1.31 | 1.21 | 1.26 | 1.05 | 1.52 | 1.22 | 2.27 | 2.14 | 1.11 | 1.58 | 1.45 |
| 11.59661 | 37.38431 | WS50M_MIN | 2012 | 1.29 | 1.9 | 1.22 | 1.43 | 1.85 | 1.34 | 1.56 | 1.27 | 1.65 | 2.08 | 1.23 | 1.11 | 1.49 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 11.59661 | 37.38431 | WS50M_MIN | 2013 | 1.02 | 1.46 | 1.15 | 1.21 | 1.58 | 1.23 | 1.92 | 1.83 | 1.31 | 1.75 | 1.65 | 0.81 | 1.41 |
| 11.59661 | 37.38431 | WS50M_MIN | 2014 | 1.18 | 1.2 | 1.03 | 1.72 | 1.62 | 1.83 | 1.48 | 1.35 | 1.46 | 1.47 | 1.49 | 1.05 | 1.41 |
| 11.59661 | 37.38431 | WS50M_MIN | 2015 | 1.04 | 1.36 | 1.23 | 1.16 | 1.83 | 1.76 | 1.18 | 1.26 | 1.22 | 1.52 | 1.68 | 1.12 | 1.36 |
| 11.59661 | 37.38431 | WS50M_MIN | 2016 | 0.97 | 1.22 | 1.14 | 1.4 | 1.88 | 1.13 | 1.74 | 1.66 | 1.41 | 1.46 | 0.91 | 1.78 | 1.39 |
| 11.59661 | 37.38431 | WS50M_MIN | 2017 | 1.07 | 0.97 | 1.2 | 1.76 | 1.33 | 1.63 | 1.3 | 1.66 | 1.68 | 1.82 | 1.57 | 1.09 | 1.42 |
| 11.59661 | 37.38431 | WS50M_MIN | 2018 | 1.12 | 1.4 | 1.37 | 1.82 | 1.95 | 1.23 | 2.03 | 1.45 | 1.31 | 1.27 | 1.08 | 1.16 | 1.43 |
| 11.59661 | 37.38431 | WS10M_MIN | 2000 | 0.92 | 0.67 | 0.89 | 1.5 | 0.72 | 1.04 | 1.4 | 1.31 | 1.06 | 0.87 | 0.94 | 0.74 | 1.01 |
| 11.59661 | 37.38431 | WS10M_MIN | 2001 | 0.91 | 0.82 | 0.89 | 1.4 | 0.86 | 1.11 | 1.22 | 1.54 | 0.95 | 1.54 | 1.03 | 0.88 | 1.1 |
| 11.59661 | 37.38431 | WS10M_MIN | 2002 | 0.86 | 0.98 | 0.76 | 1.46 | 0.85 | 1.11 | 0.95 | 0.86 | 1.19 | 1.59 | 1.04 | 0.95 | 1.05 |
| 11.59661 | 37.38431 | WS10M_MIN | 2003 | 0.94 | 0.94 | 0.73 | 1.25 | 1.15 | 1.11 | 1.49 | 1.68 | 0.89 | 1.44 | 0.94 | 1.15 | 1.15 |
| 11.59661 | 37.38431 | WS10M_MIN | 2004 | 0.97 | 0.98 | 0.91 | 1.31 | 1.4 | 0.78 | 0.9 | 1.07 | 1.31 | 1.36 | 1.08 | 0.77 | 1.07 |
| 11.59661 | 37.38431 | WS10M_MIN | 2005 | 1.38 | 1.02 | 1.06 | 0.98 | 0.95 | 1.04 | 1.33 | 1.14 | 1.18 | 1.44 | 1.01 | 0.63 | 1.1 |
| 11.59661 | 37.38431 | WS10M_MIN | 2006 | 1.16 | 0.99 | 0.96 | 0.79 | 1.23 | 0.92 | 1.08 | 1.14 | 0.82 | 1.49 | 1.08 | 1.01 | 1.06 |
| 11.59661 | 37.38431 | WS10M_MIN | 2007 | 0.92 | 0.92 | 1.07 | 1 | 1.27 | 0.99 | 1.63 | 1.1 | 1.1 | 1.57 | 1.26 | 1.2 | 1.17 |
| 11.59661 | 37.38431 | WS10M_MIN | 2008 | 1.01 | 1.42 | 1.37 | 1.26 | 1.13 | 1.11 | 1.06 | 0.84 | 0.96 | 1.6 | 0.96 | 0.68 | 1.12 |
| 11.59661 | 37.38431 | WS10M_MIN | 2009 | 0.76 | 0.72 | 0.97 | 1.38 | 1.61 | 0.92 | 1.15 | 1.12 | 1.05 | 1.77 | 1.01 | 0.9 | 1.12 |
| 11.59661 | 37.38431 | WS10M_MIN | 2010 | 0.7 | 1.26 | 1.08 | 0.97 | 0.84 | 0.88 | 1.44 | 1.22 | 1.02 | 1.84 | 0.83 | 0.9 | 1.08 |
| 11.59661 | 37.38431 | WS10M_MIN | 2011 | 0.94 | 1.39 | 1.11 | 1.04 | 0.95 | 0.81 | 1.13 | 0.92 | 1.65 | 1.58 | 0.91 | 1.28 | 1.14 |
| 11.59661 | 37.38431 | WS10M_MIN | 2012 | 1.12 | 1.56 | 1.1 | 1.2 | 1.31 | 1.03 | 1.27 | 1.14 | 1.28 | 1.56 | 1.01 | 0.93 | 1.21 |
| 11.59661 | 37.38431 | WS10M_MIN | 2013 | 0.89 | 1.23 | 0.99 | 0.99 | 1.16 | 1 | 1.49 | 1.38 | 1.04 | 1.41 | 1.35 | 0.68 | 1.13 |
| 11.59661 | 37.38431 | WS10M_MIN | 2014 | 0.98 | 1.03 | 0.91 | 1.29 | 1.14 | 1.33 | 1.18 | 1.15 | 1.1 | 1.22 | 1.21 | 0.89 | 1.12 |
| 11.59661 | 37.38431 | WS10M_MIN | 2015 | 0.88 | 1.18 | 1.05 | 0.98 | 1.34 | 1.27 | 0.92 | 0.97 | 0.92 | 1.19 | 1.39 | 0.98 | 1.09 |
| 11.59661 | 37.38431 | WS10M_MIN | 2016 | 0.84 | 1.07 | 0.97 | 1.08 | 1.38 | 0.92 | 1.34 | 1.31 | 1.08 | 1.23 | 0.73 | 1.35 | 1.11 |
| 11.59661 | 37.38431 | WS10M_MIN | 2017 | 0.9 | 0.9 | 1.04 | 1.46 | 1.03 | 1.2 | 1.12 | 1.37 | 1.25 | 1.4 | 1.29 | 0.86 | 1.15 |
| 11.59661 | 37.38431 | WS10M_MIN | 2018 | 0.99 | 1.19 | 1.14 | 1.5 | 1.42 | 0.97 | 1.58 | 1.08 | 0.96 | 1.05 | 0.9 | 1 | 1.15 |
| 11.59661 | 37.38431 | WS50M_MAX | 2000 | 6.25 | 6.87 | 7.18 | 6.76 | 6.83 | 6.39 | 5.03 | 5.47 | 4.28 | 4.42 | 5.66 | 5.2 | 5.86 |
| 11.59661 | 37.38431 | WS50M_MAX | 2001 | 7 | 6.43 | 6.94 | 6.58 | 5.98 | 5.27 | 5.01 | 5.66 | 4.25 | 4.87 | 6 | 5.61 | 5.8 |
| 11.59661 | 37.38431 | WS50M_MAX | 2002 | 6.69 | 6.99 | 5.96 | 7.05 | 7.09 | 5.78 | 5.03 | 4.52 | 4.4 | 6.02 | 5.61 | 6.84 | 5.99 |
| 11.59661 | 37.38431 | WS50M_MAX | 2003 | 7.21 | 6.47 | 6.13 | 7.38 | 6.66 | 6.37 | 5.29 | 5.41 | 4.42 | 6.02 | 6.26 | 6.79 | 6.2 |
| 11.59661 | 37.38431 | WS50M_MAX | 2004 | 7.3 | 7.57 | 6.8 | 6.06 | 7.01 | 5.88 | 5.13 | 5.17 | 4.79 | 6.74 | 5.88 | 6.61 | 6.24 |
| 11.59661 | 37.38431 | WS50M_MAX | 2005 | 7.21 | 7.07 | 6.45 | 6.47 | 6.57 | 6.3 | 5.29 | 4.93 | 4.62 | 4.96 | 6.1 | 6.59 | 6.04 |

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|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 11.59661 | 37.38431 | WS50M_MAX | 2006 | 6.9 | 6.93 | 7.02 | 6.09 | 6.05 | 5.91 | 4.84 | 4.96 | 4.13 | 5.53 | 5.55 | 5.6 | 5.79 |
| 11.59661 | 37.38431 | WS50M_MAX | 2007 | 6.27 | 6.63 | 7.4 | 6.61 | 6.14 | 5.79 | 5.3 | 4.6 | 4.61 | 5.76 | 6.66 | 6.65 | 6.03 |
| 11.59661 | 37.38431 | WS50M_MAX | 2008 | 6.24 | 7.45 | 7.36 | 6.51 | 6.01 | 6.09 | 5.19 | 4.39 | 4.37 | 5.22 | 5.15 | 4.99 | 5.74 |
| 11.59661 | 37.38431 | WS50M_MAX | 2009 | 6.42 | 5.89 | 6.32 | 6.43 | 7.42 | 6.46 | 4.7 | 4.68 | 4.25 | 5.27 | 6.04 | 5.7 | 5.8 |
| 11.59661 | 37.38431 | WS50M_MAX | 2010 | 5.35 | 7.29 | 7.06 | 5.65 | 6.06 | 5.95 | 5.41 | 5.09 | 4.24 | 5.48 | 4.85 | 5.16 | 5.62 |
| 11.59661 | 37.38431 | WS50M_MAX | 2011 | 6.54 | 7.82 | 6.38 | 6.04 | 5.95 | 5.47 | 5.2 | 5.02 | 4.75 | 6.1 | 5.64 | 6.52 | 5.94 |
| 11.59661 | 37.38431 | WS50M_MAX | 2012 | 7.11 | 7.99 | 7 | 7.43 | 6.65 | 6.63 | 5.28 | 4.98 | 4.85 | 5.57 | 4.5 | 5.8 | 6.14 |
| 11.59661 | 37.38431 | WS50M_MAX | 2013 | 6.12 | 7.37 | 7.4 | 7.27 | 6.43 | 5.72 | 5.42 | 5.11 | 4.31 | 4.66 | 5.4 | 5.53 | 5.88 |
| 11.59661 | 37.38431 | WS50M_MAX | 2014 | 5.9 | 7.43 | 6.19 | 6.11 | 5.41 | 6.04 | 5.44 | 4.78 | 4.74 | 5.04 | 5.53 | 5.64 | 5.67 |
| 11.59661 | 37.38431 | WS50M_MAX | 2015 | 6.19 | 6.63 | 6.6 | 6.46 | 6.4 | 6.13 | 5.28 | 4.94 | 4.45 | 5.79 | 5.66 | 5.76 | 5.85 |
| 11.59661 | 37.38431 | WS50M_MAX | 2016 | 6.8 | 7.27 | 6.44 | 6.54 | 5.29 | 6.14 | 5.4 | 5.08 | 4.76 | 5.01 | 5.75 | 6.8 | 5.93 |
| 11.59661 | 37.38431 | WS50M_MAX | 2017 | 6.86 | 6.17 | 6.66 | 6.53 | 4.8 | 6.1 | 5.45 | 5.41 | 4.89 | 5.02 | 5.27 | 5.87 | 5.75 |
| 11.59661 | 37.38431 | WS50M_MAX | 2018 | 7.16 | 6.49 | 7 | 6.55 | 7.11 | 5.86 | 5.35 | 5.01 | 4.57 | 5.3 | 5.33 | 5.5 | 5.93 |
| 11.59661 | 37.38431 | WS10M_MAX | 2000 | 4.52 | 4.87 | 5.48 | 5.31 | 5.49 | 5.14 | 3.98 | 4.01 | 3.24 | 3.1 | 4.08 | 3.76 | 4.41 |
| 11.59661 | 37.38431 | WS10M_MAX | 2001 | 4.6 | 4.73 | 5.33 | 5.08 | 4.67 | 4.23 | 3.95 | 4.41 | 3.27 | 3.65 | 4.41 | 4.03 | 4.36 |
| 11.59661 | 37.38431 | WS10M_MAX | 2002 | 4.67 | 5.05 | 4.69 | 5.66 | 5.29 | 4.99 | 4.17 | 3.46 | 3.44 | 4.31 | 3.87 | 4.8 | 4.53 |
| 11.59661 | 37.38431 | WS10M_MAX | 2003 | 4.9 | 4.87 | 4.83 | 5.58 | 5.21 | 5.18 | 4.15 | 4.15 | 3.32 | 4.36 | 4.58 | 4.8 | 4.66 |
| 11.59661 | 37.38431 | WS10M_MAX | 2004 | 5.04 | 5.89 | 5.1 | 4.81 | 5.43 | 4.95 | 4.07 | 3.87 | 3.54 | 4.83 | 4.17 | 4.3 | 4.66 |
| 11.59661 | 37.38431 | WS10M_MAX | 2005 | 5.2 | 5.13 | 4.66 | 4.92 | 4.81 | 5.05 | 4.19 | 3.64 | 3.43 | 3.66 | 4.42 | 4.93 | 4.5 |
| 11.59661 | 37.38431 | WS10M_MAX | 2006 | 5.09 | 4.84 | 4.94 | 4.75 | 4.85 | 4.56 | 3.78 | 3.77 | 3.13 | 3.98 | 3.95 | 3.95 | 4.3 |
| 11.59661 | 37.38431 | WS10M_MAX | 2007 | 4.44 | 4.57 | 5.4 | 5.09 | 4.77 | 4.78 | 4.25 | 3.35 | 3.43 | 4.29 | 5.01 | 4.91 | 4.53 |
| 11.59661 | 37.38431 | WS10M_MAX | 2008 | 4.73 | 5.43 | 5.24 | 5.14 | 4.61 | 4.96 | 4.18 | 3.32 | 3.36 | 3.86 | 3.81 | 3.85 | 4.37 |
| 11.59661 | 37.38431 | WS10M_MAX | 2009 | 4.61 | 4.4 | 4.66 | 5.14 | 5.47 | 5.06 | 3.7 | 3.54 | 3.26 | 4.02 | 4.35 | 4.11 | 4.36 |
| 11.59661 | 37.38431 | WS10M_MAX | 2010 | 3.86 | 5.61 | 5.4 | 4.29 | 4.9 | 4.73 | 4.22 | 3.84 | 3.19 | 4.17 | 3.53 | 3.89 | 4.3 |
| 11.59661 | 37.38431 | WS10M_MAX | 2011 | 4.67 | 5.58 | 4.84 | 4.73 | 4.75 | 4.38 | 3.97 | 3.86 | 3.47 | 4.44 | 3.86 | 4.54 | 4.42 |
| 11.59661 | 37.38431 | WS10M_MAX | 2012 | 4.72 | 5.84 | 5.24 | 5.56 | 5.27 | 5.39 | 4.05 | 3.58 | 3.53 | 4.13 | 3.19 | 4.17 | 4.55 |
| 11.59661 | 37.38431 | WS10M_MAX | 2013 | 4.44 | 5.29 | 5.6 | 5.32 | 4.95 | 4.57 | 4.46 | 3.98 | 3.22 | 3.47 | 3.88 | 4.04 | 4.43 |
| 11.59661 | 37.38431 | WS10M_MAX | 2014 | 4.28 | 5.4 | 4.64 | 4.7 | 4.11 | 4.48 | 4.06 | 3.47 | 3.41 | 3.74 | 3.99 | 4.04 | 4.18 |
| 11.59661 | 37.38431 | WS10M_MAX | 2015 | 4.28 | 4.73 | 4.96 | 5 | 5.08 | 5.03 | 4.01 | 3.53 | 3.34 | 4.33 | 4.01 | 3.94 | 4.35 |
| 11.59661 | 37.38431 | WS10M_MAX | 2016 | 5.05 | 4.96 | 4.65 | 5.16 | 4.19 | 4.79 | 4.08 | 3.77 | 3.53 | 3.69 | 4.23 | 4.95 | 4.42 |
| 11.59661 | 37.38431 | WS10M_MAX | 2017 | 5.01 | 4.69 | 4.93 | 4.93 | 3.76 | 4.64 | 4.14 | 3.85 | 3.57 | 3.69 | 3.69 | 4.15 | 4.25 |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 11.59661 | 37.38431 | WS10M_MAX | 2018 | 4.9 | 4.65 | 5.17 | 4.89 | 5.92 | 4.74 | 4.01 | 3.73 | 3.62 | 3.93 | 4.04 | 3.99 | 4.47 |
| 11.59661 | 37.38431 | WS50M | 2000 | 3.34 | 3.65 | 3.98 | 4.1 | 3.68 | 3.76 | 3.55 | 3.5 | 2.88 | 2.77 | 3.34 | 3 | 3.46 |
| 11.59661 | 37.38431 | WS50M | 2001 | 3.66 | 3.46 | 3.98 | 4.22 | 3.43 | 3.46 | 3.39 | 3.87 | 2.85 | 3.35 | 3.62 | 3.34 | 3.55 |
| 11.59661 | 37.38431 | WS50M | 2002 | 3.77 | 3.9 | 3.58 | 4.59 | 4.04 | 3.89 | 3.45 | 2.99 | 2.96 | 3.86 | 3.43 | 3.83 | 3.69 |
| 11.59661 | 37.38431 | WS50M | 2003 | 3.89 | 3.8 | 3.65 | 4.19 | 4 | 3.82 | 3.73 | 3.82 | 3 | 3.63 | 3.7 | 3.92 | 3.76 |
| 11.59661 | 37.38431 | WS50M | 2004 | 4.09 | 4.32 | 3.85 | 3.86 | 4.38 | 3.43 | 3.24 | 3.18 | 3.29 | 4.32 | 3.37 | 3.7 | 3.75 |
| 11.59661 | 37.38431 | WS50M | 2005 | 4.31 | 4.09 | 3.74 | 3.85 | 3.77 | 3.77 | 3.55 | 3.18 | 3.19 | 3.3 | 3.67 | 3.32 | 3.64 |
| 11.59661 | 37.38431 | WS50M | 2006 | 3.96 | 3.83 | 3.88 | 3.44 | 3.73 | 3.59 | 3.23 | 3.26 | 2.66 | 3.53 | 3.44 | 3.28 | 3.49 |
| 11.59661 | 37.38431 | WS50M | 2007 | 3.59 | 3.73 | 4.13 | 3.79 | 3.92 | 3.54 | 3.77 | 3.1 | 3.14 | 3.6 | 3.9 | 3.69 | 3.66 |
| 11.59661 | 37.38431 | WS50M | 2008 | 3.64 | 4.4 | 4.32 | 4.14 | 3.65 | 3.65 | 3.39 | 2.82 | 2.91 | 3.52 | 2.93 | 2.72 | 3.5 |
| 11.59661 | 37.38431 | WS50M | 2009 | 3.5 | 3.3 | 3.67 | 4.18 | 4.39 | 3.66 | 3.2 | 3.15 | 3 | 3.72 | 3.57 | 3.36 | 3.56 |
| 11.59661 | 37.38431 | WS50M | 2010 | 3.22 | 4.38 | 4.09 | 3.32 | 3.6 | 3.4 | 3.64 | 3.43 | 2.95 | 3.72 | 2.86 | 3.08 | 3.47 |
| 11.59661 | 37.38431 | WS50M | 2011 | 3.81 | 4.42 | 3.78 | 3.61 | 3.61 | 3.37 | 3.31 | 3.23 | 3.53 | 3.83 | 3.21 | 3.82 | 3.62 |
| 11.59661 | 37.38431 | WS50M | 2012 | 4.09 | 4.71 | 4.01 | 4.33 | 4.3 | 3.92 | 3.46 | 3.23 | 3.34 | 3.72 | 2.78 | 3.42 | 3.77 |
| 11.59661 | 37.38431 | WS50M | 2013 | 3.51 | 4.17 | 4.09 | 3.9 | 4.01 | 3.55 | 3.73 | 3.54 | 2.96 | 3.19 | 3.49 | 3.22 | 3.61 |
| 11.59661 | 37.38431 | WS50M | 2014 | 3.57 | 4.23 | 3.57 | 3.96 | 3.44 | 3.91 | 3.57 | 3.12 | 3.21 | 3.29 | 3.42 | 3.28 | 3.54 |
| 11.59661 | 37.38431 | WS50M | 2015 | 3.44 | 3.74 | 3.73 | 3.69 | 4.03 | 3.96 | 3.26 | 3.07 | 2.94 | 3.56 | 3.56 | 3.56 | 3.54 |
| 11.59661 | 37.38431 | WS50M | 2016 | 4.03 | 4.1 | 3.6 | 4.07 | 3.57 | 3.72 | 3.61 | 3.37 | 3.08 | 3.28 | 3.19 | 4.02 | 3.63 |
| 11.59661 | 37.38431 | WS50M | 2017 | 3.58 | 3.75 | 3.8 | 3.93 | 3.1 | 3.74 | 3.54 | 3.49 | 3.32 | 3.32 | 3.27 | 3.2 | 3.5 |
| 11.59661 | 37.38431 | WS50M | 2018 | 3.91 | 3.75 | 4.03 | 4.01 | 4.42 | 3.68 | 3.74 | 3.28 | 3.05 | 3.36 | 3.32 | 3.46 | 3.67 |
| 11.59661 | 37.38431 | WS10M | 2000 | 2.49 | 2.73 | 3.13 | 3.16 | 2.93 | 2.92 | 2.71 | 2.65 | 2.17 | 2.05 | 2.45 | 2.26 | 2.64 |
| 11.59661 | 37.38431 | WS10M | 2001 | 2.75 | 2.69 | 3.06 | 3.22 | 2.7 | 2.66 | 2.6 | 2.92 | 2.15 | 2.52 | 2.66 | 2.46 | 2.7 |
| 11.59661 | 37.38431 | WS10M | 2002 | 2.82 | 2.98 | 2.77 | 3.54 | 3.18 | 3.05 | 2.62 | 2.23 | 2.24 | 2.8 | 2.49 | 2.83 | 2.79 |
| 11.59661 | 37.38431 | WS10M | 2003 | 2.9 | 2.92 | 2.83 | 3.26 | 3.16 | 2.99 | 2.84 | 2.89 | 2.22 | 2.68 | 2.7 | 2.84 | 2.85 |
| 11.59661 | 37.38431 | WS10M | 2004 | 3.04 | 3.31 | 2.97 | 2.99 | 3.4 | 2.7 | 2.46 | 2.39 | 2.43 | 3.06 | 2.46 | 2.69 | 2.82 |
| 11.59661 | 37.38431 | WS10M | 2005 | 3.21 | 3.07 | 2.89 | 2.99 | 2.92 | 2.94 | 2.71 | 2.4 | 2.37 | 2.47 | 2.68 | 2.46 | 2.76 |
| 11.59661 | 37.38431 | WS10M | 2006 | 2.93 | 2.9 | 2.97 | 2.65 | 2.91 | 2.73 | 2.46 | 2.46 | 2 | 2.6 | 2.54 | 2.43 | 2.63 |
| 11.59661 | 37.38431 | WS10M | 2007 | 2.69 | 2.79 | 3.15 | 2.88 | 2.99 | 2.77 | 2.87 | 2.32 | 2.34 | 2.68 | 2.83 | 2.72 | 2.75 |
| 11.59661 | 37.38431 | WS10M | 2008 | 2.75 | 3.33 | 3.28 | 3.13 | 2.82 | 2.83 | 2.59 | 2.1 | 2.19 | 2.61 | 2.2 | 2.08 | 2.66 |
| 11.59661 | 37.38431 | WS10M | 2009 | 2.63 | 2.51 | 2.81 | 3.26 | 3.35 | 2.84 | 2.46 | 2.36 | 2.27 | 2.77 | 2.59 | 2.51 | 2.7 |
| 11.59661 | 37.38431 | WS10M | 2010 | 2.44 | 3.37 | 3.13 | 2.53 | 2.81 | 2.61 | 2.79 | 2.59 | 2.18 | 2.78 | 2.16 | 2.34 | 2.64 |

| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 11.59661 | 37.38431 | WS10M | 2011 | 2.85 | 3.31 | 2.93 | 2.82 | 2.82 | 2.59 | 2.52 | 2.43 | 2.59 | 2.81 | 2.35 | 2.79 | 2.73 |
| 11.59661 | 37.38431 | WS10M | 2012 | 2.99 | 3.46 | 3.09 | 3.37 | 3.31 | 3.07 | 2.65 | 2.4 | 2.48 | 2.74 | 2.09 | 2.53 | 2.85 |
| 11.59661 | 37.38431 | WS10M | 2013 | 2.64 | 3.13 | 3.17 | 3.06 | 3.08 | 2.74 | 2.86 | 2.67 | 2.2 | 2.39 | 2.57 | 2.41 | 2.74 |
| 11.59661 | 37.38431 | WS10M | 2014 | 2.69 | 3.23 | 2.72 | 3.03 | 2.62 | 2.93 | 2.69 | 2.34 | 2.37 | 2.44 | 2.54 | 2.44 | 2.66 |
| 11.59661 | 37.38431 | WS10M | 2015 | 2.55 | 2.81 | 2.84 | 2.92 | 3.12 | 3.1 | 2.47 | 2.28 | 2.19 | 2.6 | 2.61 | 2.59 | 2.67 |
| 11.59661 | 37.38431 | WS10M | 2016 | 3.03 | 3.07 | 2.74 | 3.19 | 2.73 | 2.87 | 2.75 | 2.54 | 2.29 | 2.45 | 2.38 | 2.94 | 2.75 |
| 11.59661 | 37.38431 | WS10M | 2017 | 2.66 | 2.86 | 2.89 | 2.97 | 2.37 | 2.89 | 2.7 | 2.63 | 2.45 | 2.47 | 2.43 | 2.4 | 2.64 |
| 11.59661 | 37.38431 | WS10M | 2018 | 2.94 | 2.83 | 3.12 | 3.11 | 3.54 | 2.88 | 2.85 | 2.48 | 2.28 | 2.46 | 2.44 | 2.54 | 2.79 |
| 11.59661 | 37.38431 | QV2M | 2000 | 8.5 | 8.17 | 8.6 | 9.67 | 11.04 | 12.61 | 13.11 | 13.34 | 13.02 | 12.33 | 10.12 | 9.17 | 10.82 |
| 11.59661 | 37.38431 | QV2M | 2001 | 7.73 | 8.51 | 7.59 | 10.02 | 10.79 | 12.11 | 12.83 | 13.55 | 12.77 | 11.68 | 8.98 | 9.22 | 10.49 |
| 11.59661 | 37.38431 | QV2M | 2002 | 8.54 | 7.85 | 9.02 | 9.23 | 7.81 | 12.29 | 13.11 | 13.16 | 12.41 | 10.31 | 9.4 | 8.39 | 10.14 |
| 11.59661 | 37.38431 | QV2M | 2003 | 6.74 | 7.9 | 8.53 | 7.11 | 8.11 | 12.15 | 13.08 | 13.65 | 13.24 | 10.23 | 9.11 | 7.85 | 9.82 |
| 11.59661 | 37.38431 | QV2M | 2004 | 7.7 | 7.53 | 6.85 | 9.68 | 9.54 | 12.01 | 12.83 | 13.32 | 12.89 | 10.25 | 9.55 | 8.86 | 10.09 |
| 11.59661 | 37.38431 | QV2M | 2005 | 7.17 | 7 | 8.34 | 8.32 | 9.51 | 12.93 | 13.06 | 13.64 | 13.42 | 11.12 | 9.09 | 6.71 | 10.04 |
| 11.59661 | 37.38431 | QV2M | 2006 | 7.26 | 7.41 | 7.59 | 9.17 | 11.69 | 12.48 | 13.36 | 13.62 | 12.84 | 11.32 | 10.13 | 9.86 | 10.58 |
| 11.59661 | 37.38431 | QV2M | 2007 | 8.85 | 8.2 | 8.34 | 9.72 | 11.41 | 13 | 13.39 | 13.58 | 13.13 | 10.02 | 8.96 | 6.71 | 10.45 |
| 11.59661 | 37.38431 | QV2M | 2008 | 8.56 | 6.9 | 5.66 | 9.51 | 11.32 | 12.63 | 13.17 | 13.51 | 13 | 11.21 | 9.07 | 8.47 | 10.26 |
| 11.59661 | 37.38431 | QV2M | 2009 | 7.38 | 8.29 | 8.62 | 8.9 | 8.55 | 12.47 | 13.14 | 13.84 | 12.49 | 10.81 | 9.01 | 8.94 | 10.21 |
| 11.59661 | 37.38431 | QV2M | 2010 | 8.03 | 7.31 | 7.9 | 10.43 | 12.31 | 13.22 | 13.35 | 13.78 | 13.29 | 11 | 9.63 | 8.48 | 10.74 |
| 11.59661 | 37.38431 | QV2M | 2011 | 8.34 | 6.3 | 7.86 | 8.47 | 11.2 | 12.97 | 12.99 | 13.45 | 12.85 | 10.29 | 10.01 | 7.93 | 10.25 |
| 11.59661 | 37.38431 | QV2M | 2012 | 7.72 | 5.73 | 7.04 | 6.65 | 10.59 | 12.03 | 13.37 | 13.83 | 13.35 | 10.61 | 10.76 | 9.06 | 10.08 |
| 11.59661 | 37.38431 | QV2M | 2013 | 8.23 | 7.07 | 7.43 | 7.52 | 11.76 | 12.82 | 13.08 | 13.46 | 13.12 | 11.59 | 10.72 | 8.07 | 10.43 |
| 11.59661 | 37.38431 | QV2M | 2014 | 8.2 | 7.48 | 9.66 | 10.27 | 12.67 | 12.82 | 13.62 | 13.66 | 13.19 | 11.87 | 10.3 | 8.71 | 11.06 |
| 11.59661 | 37.38431 | QV2M | 2015 | 8.07 | 7.04 | 8.13 | 8.01 | 11.62 | 12.49 | 13.35 | 13.89 | 13.29 | 11.96 | 11.22 | 11.1 | 10.87 |
| 11.59661 | 37.38431 | QV2M | 2016 | 8.87 | 8.25 | 9.08 | 8.3 | 12.87 | 13.12 | 13.57 | 13.52 | 13.17 | 11.33 | 8.38 | 7.26 | 10.66 |
| 11.59661 | 37.38431 | QV2M | 2017 | 5.4 | 9.16 | 8.4 | 9.98 | 12.87 | 13.32 | 13.89 | 14 | 13.64 | 12.19 | 10.01 | 7.21 | 10.84 |
| 11.59661 | 37.38431 | QV2M | 2018 | 7.47 | 7.7 | 7.02 | 8.47 | 10.69 | 12.84 | 13.37 | 13.44 | 12.76 | 11.82 | 10.57 | 9.79 | 10.51 |

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Urban Design and Development

# Investigating the Optimum Building Density and Lake Tana's Breeze in the Case of Bahir Dar city, Ethiopia

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*The ideal built-up density for proper ventilation of Bahir Dar city is proposed using a method of performing city-scale ventilation assessment based on remote sensing, GIS, and CFD technology. The ventilation of a city depends on the location and background ventilation source. Bahir Dar is a city found south side of Lake Tana and beginning of River Abay. The ventilation background is assessed using meteorological data of wind direction and speed. The numerical simulation of ventilation potential index performance have done using roughness length (RL), sky view factor (SVF) and computational fluid dynamics (CFD). In this study, the roughness length (RL) determined the land use land cover of land sat 8 and the building morphology of existing development. The sky view factor (SVF) is estimated and calculated by using 30m high resolution digital elevation model by SAGA GIS. The general wind pattern and ventilation of the existing high rise building is evaluated by CFD simulation. Generally, the existing ventilation performance of Bahir*

*Dar is relatively high. But in the southern part of the city ventilation is moderate (general) and low. The new structure plan of Bahir Dar city have been checked by the above criteria and the result shows high roughness length and low ventilation performance because of high density development proposal and block Lake Tana breez's. Suitability map developed by using multiple criteria; exiting ventilation potential, major ventilation source, urban ventilation corridor buffering standard and sky view factor have been used to produce suitability map of urban ventilation corridor design. The ventilation corridor design result perform a ventilation potential index value 0.4 with low roughness value of 0.5 and high sky view factor 0.67. Accordingly, the municipality of Bahir Dar should adopt an optimal citywide development density of not more than 50%, a minimum of 15m distance between buildings, and a maximum building size (footprint) of 20m x30m.*

**Key Words**: - Ventilation potential index, Suitability map, ventilation corridor, & sky view factor

## 1. Introduction

Nowadays, humans live in a critical environmental situation characterized essentially by global warming. One of the most important indicators of this situation is the effects of heat on urban buildings and streets. Cities are growing at a fast rate with higher density, narrower urban corridors, and more high-rise urban structures. Following this, the deterioration of the urban environment becomes a scorch concern (Wong, 2015). Thus, in urban areas, the temperature is high and generates discomfort in outdoor living spaces.

The urbanization process structurally modifies natural ventilation as attested by several scientific researches that indicate that disorderly urban growth is responsible for changing local climatic parameters, compromising thermal comfort conditions. These issues are linked to urban planning (Stewart and Oke, 2006).

The process of urbanization increases the use of natural land and changing the natural ventilation process and as result decreasing the supply of fresh air for the residence of cities.

Urban form is the result of interactions between buildings' heights, the distance between buildings, and occupancy rate, changing the permeability of the wind within the urban fabric and influencing its use for passive cooling of buildings (Proceedings of Building Simulation, 2011).

Using CFD modeling to analyze the ventilation of cities is developed from time to time but most of the applications are worked in the single building passive heating and cooling system (Duarte & Serra (2003). Cities had to get passive cooling and heating system from the surrounding air. Natural ventilation area affected by the development density, size, orientation of the street system.

As Prata-Shimomura et al, (2009) attest, verifying natural ventilation conditions through models assists the architectural design and urban planning process. Wind tunnel tests, software's or mathematical models are important tools in the analysis of urban transformations, allowing greater precision in the airflow assessment in internal and external environments.

Designing ventilation corridor of Bahir Dar City for natural breeze from Lake Tana fresh air by investigating roughness length (RL), sky view factor (SVF), CFD test of urban morphology of existing city development and design ventilation corridor with high sky view factor and low roughness of city. Investigating the existing ventilation potential of Bahir Dar by roughness length (RL), sky view factor (SVF) and CFD simulation and design urban ventilation corridor with optimum built environment density of Bahir Dar for maximum ventilation potential index.

The main objective of the research is to determine the density of a city based on investigating Lake Tana's Breeze.

## 2. MATERIALS AND METHODES

### 2.1 Study Area Description

Bahir Dar is a capital city of Amhara region, found in the northern part of Ethiopia. City of Bahir Dar located at the south side of Lake Tana and beginning of River Abay at 1,820 meters above sea level. It is located 11.59 latitude and 37.39 longitudes. The city is found in a tropical climate zone with hot climate conditions. Lake Tana and River Abay makes the city important tourist destination and recreational city.

Figure 1 shows the location map of Bahir Dar city

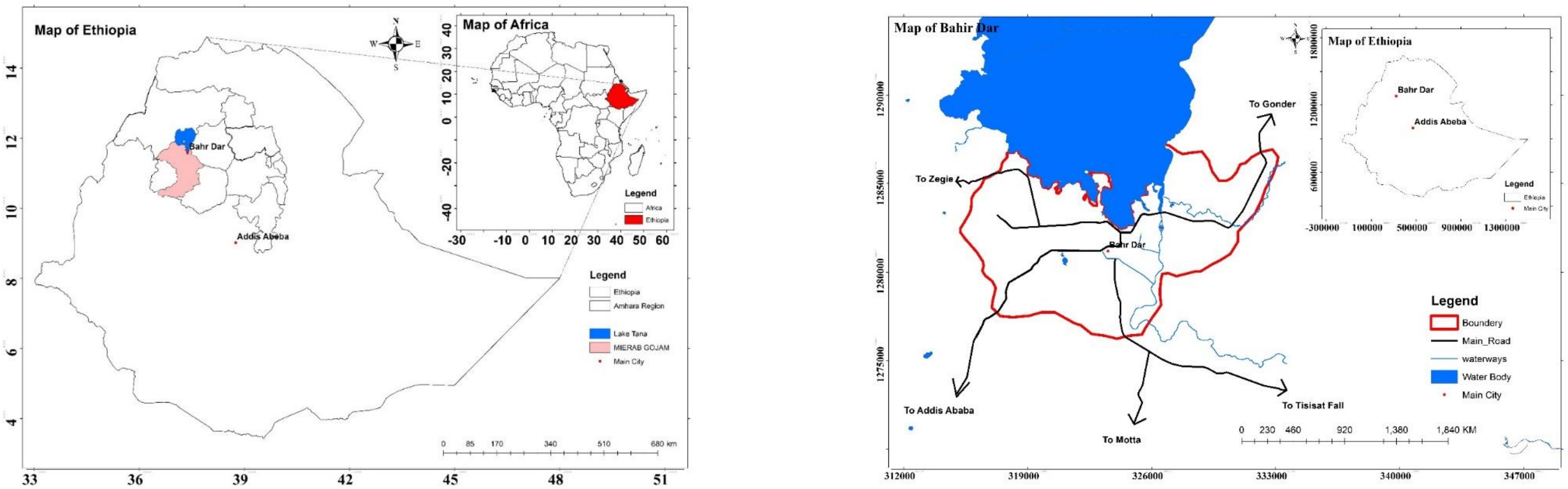

Figure 1: Location map of Bahir Dar

## 2.2 Research Design

The research design is over all process of research flows that integrates relevant component and data interpretation. This research design represents the process of this study paper. Figure 2 shows the combination of instrument and material used in the overall research process.

The prevailing wind direction of Bahir Dar is towards southeast during dry season and towards northwest during rainy. The main ventilation sources of Bahir Dar is monsoon wind that flows from Lake Tana to Bahir Dar. This study main concern is the ventilation of dry season for city of Bahir Dar. Figure 12 shows the wind direction of Bahir Dar in winter and summer season.

**The overall flow of research process has been identified on the diagram.**

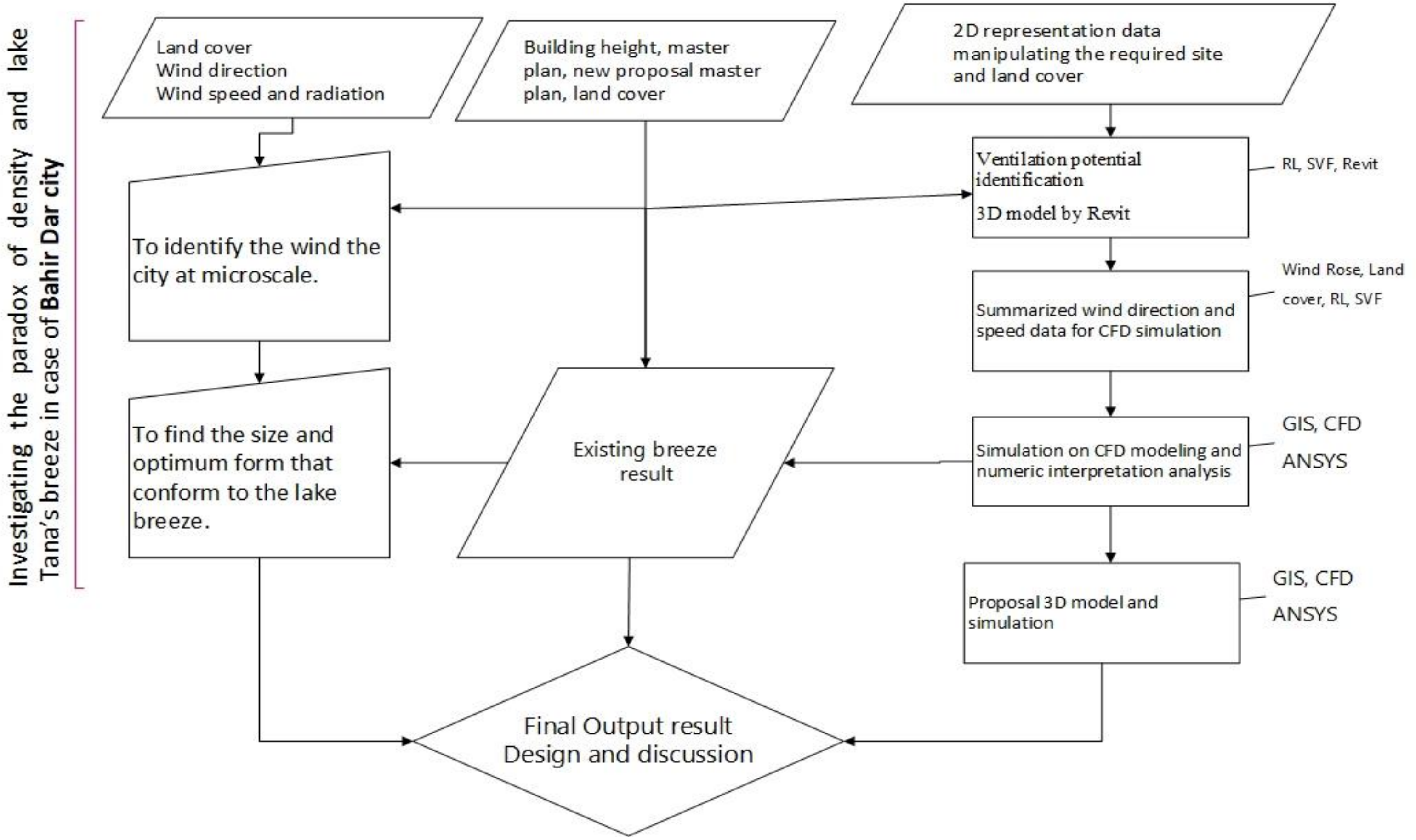

Figure 2: research design flow chart

The wind direction of the study area mostly blow within $165^0$ - $200^0$ degree of inclination. Figure 3 below shows dry season wind blow from Lake Tana to Bahir Dar. The dominance wind blows from north to south. The wind on these station point is 3.2m/s maximum and 2m/s minimum speed.

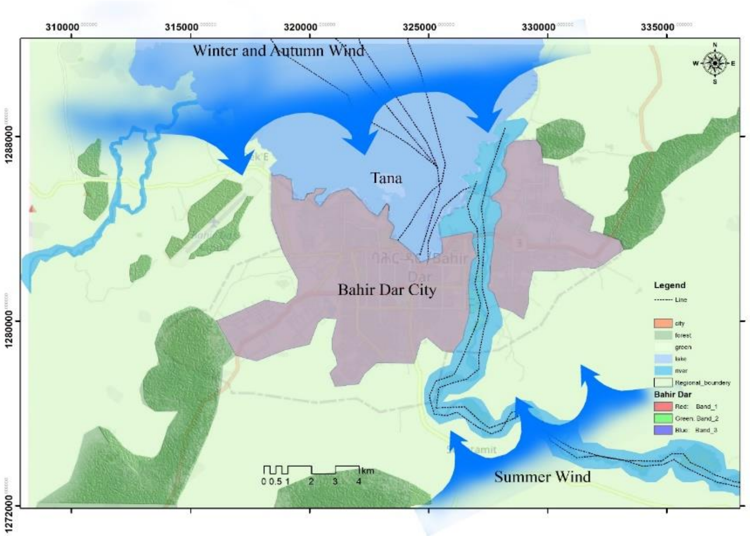

Figure 3: Wind source of Bahir Dar

## Grading the Ventilation Potential

In the study of SVF with respect of urban heat island effect urban area (Liu *et al.*, 2016) conclude that the SVF influenced the urban heat island intensity significantly. The author defined the SVF factor 0.65. Because the SVF factor exceed this value ventilation alleviates the heat island. The RL of the author 0.5. Set RL< 0.1 in highly ventilated area, such as water body and small grass. This study define the upper limit of RL > 0.6 for high density area and the lower limit is 0.1 for high ventilated area. Table 7 shows ventilation potential grading.

# 3 RESULT

## 3.1 Estimating the ventilation potential at Bahir Dar city

Figure 4 shows the ventilation potential distribution of Bahir Dar city from 2020 DEM 30m resolution. The ventilation potential in the northern and southern side of Bahir Dar plain is very high, and there is no ventilation blocks before construction. Dry season wind flows from north to south is very suitable to cool Bahir Dar.

Figure 4 shows the ventilation potential distribution of Bahir Dar city existing development 30m resolution. The ventilation potential in the northern side of Bahir Dar plain is very high, and there is no apparent ventilation potential in relatively dense building area. In Figure 5 shows the ventilation potential in place **A** relatively low. Place **A** development will not only influence the ventilation environment but may also prevent northern air flow from entering to the southern part of Bahir Dar city. Place **A** scores high roughness 0.5 of building roughness and relatively medium SVF 0.7 with low raise building height.

Figure 6 shows the ventilation potential of new structure plan of Bahir Dar.

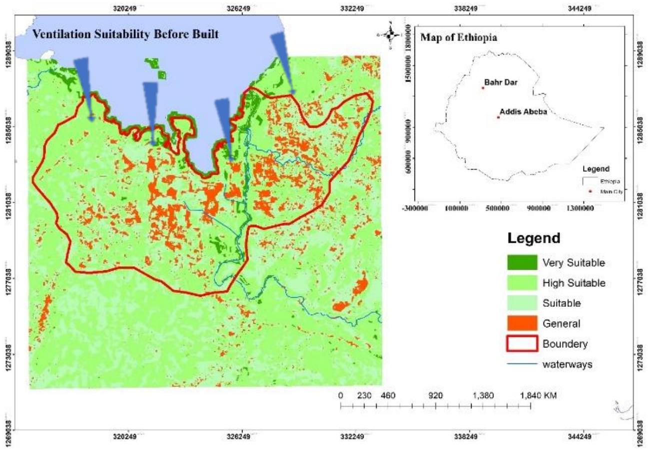

Figure 4: ventilation potential without development

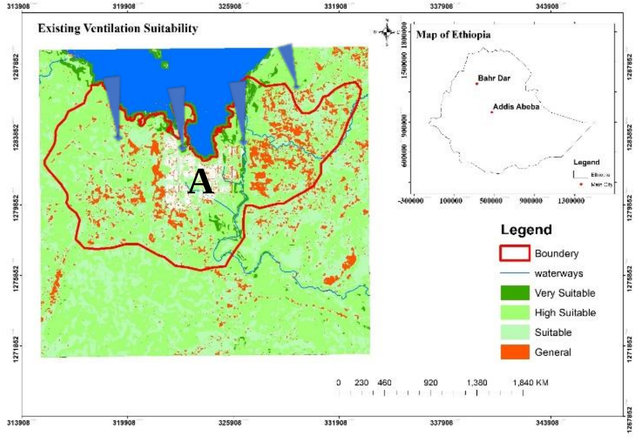

Figure 5: Ventilation potential in existing development

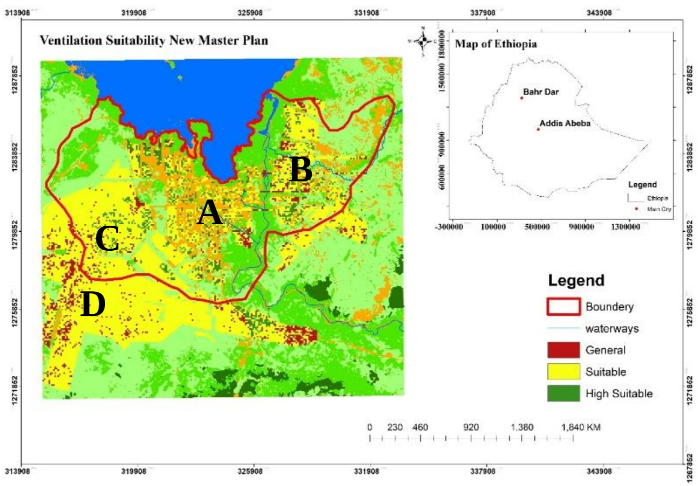

Figure 6: ventilation potential of new structure plan Bahir Dar

### 3.2 Optimum Ventilation Corridor Design

Urban ventilation corridors are formed by ecological buffer zones, greenbelts, roads, rivers, parks and green spaces (Ren *et al.*, 2018). The design of optimum ventilation corridor of Bahir Dar is design by the ventilation criteria of high ventilation performance of the city.

Calculation of building height decision by SVF

$$SVF\ canyon = \cos(\mathrm{atan}(2.H/W)) \qquad (6)$$

*H= Building height*

*W= Street width*

Table A shows *SVF by changing building height*

Table: Optimum density design by SVF

| Street width (m) | building height maximum (m) | SVF |
|---|---|---|
| 40 | 80 | 0.24 |
| 30 | 60 | 0.24 |
| 25 | 60 | 0.2 |
| 20 | 50 | 0.2 |
| 15 | 40 | 0.2 |

Criteria to get optimum ventilation corridor

| Type | Minimum | Maximum |
|---|---|---|
| Density | 40% | 55% |
| Roughness Length | 0.1 | 0.6 |
| Sky view Factor | 0.25 | 0.90 |
| Ventilation corridor length | 100 | - |
| Ventilation corridor obstacle | - | 15% |

The ventilation performance index of the final design is 0.6 after suitability analysis done. The ventilation corridor design by considering the winter wind and peak temperature value. The major city breeze is level one ventilation corridor shown by green arrows. Level one ventilation corridor design by connecting the main open space, water body and city parks as a buffer for the city. Ventilation corridor two is designed connecting small public space with Major Street of Bahir Dar. The dot grid polygon shows the ventilation obstruction corridor of city built environment (Figure 25). Inside this polygon level three ventilation have been design by greenery and local road of the city.

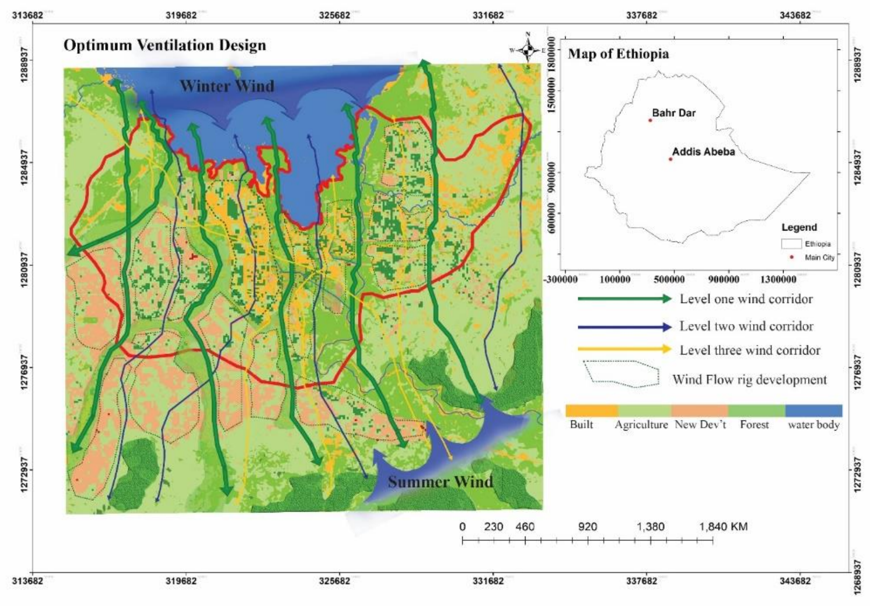

Figure 6: Ventilation corridor design

## 3.3 Estimating maximum density using ventilation corridor design by CFD

The building shape is design for maximum obstruction of wind flow and SVF shadow with a maximum size of 20m x 30m building. City center ventilation have been tested by CFD ANSYS simulation. Figure 26 shows the city center ventilation performance that is designed 50% built density. The simulation shows the ventilation between buildings is relatively high. The simulation design on the dry season wind with speed of source 3.5m/s of reference wind. The northern side of the city have get very high ventilation breeze from Lake Tana. The building height from the lake side have started from the existing building height of G+ 7 to allow the wind into city center with low obstruction.

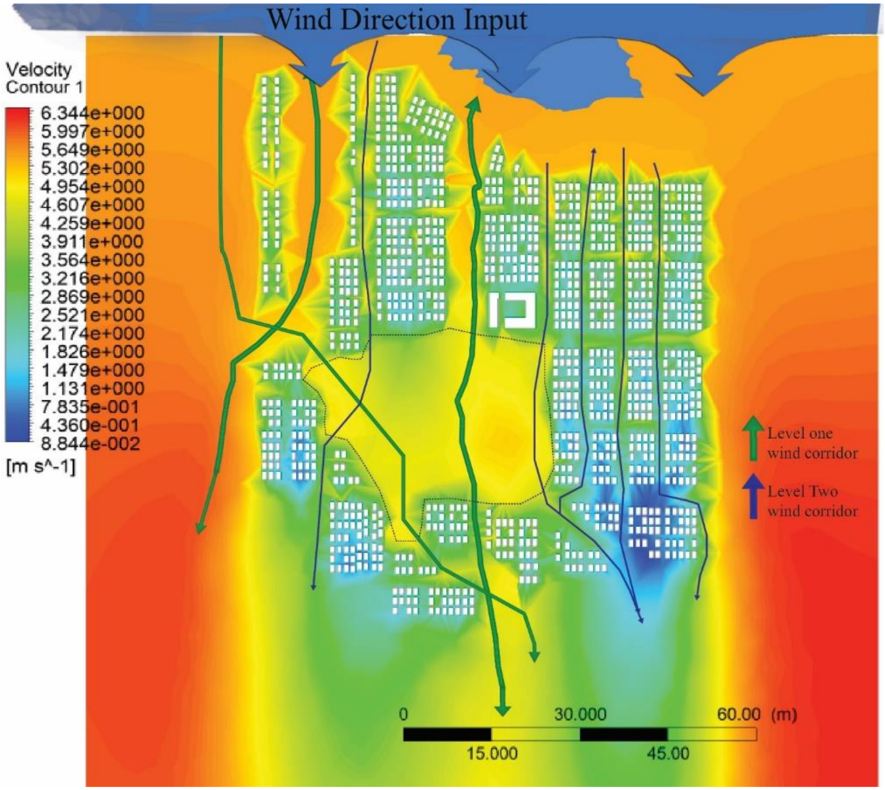

Figure 7: optimum density design

# 4 DISCUSSION

## 4.1 Estimating the Ventilation Potential of New Master Plan of Bahir Dar

Bahir Dar city has prepared a new structural plan with medium and high-density development of the city. The study test this future Bahir Dar development type. The structure plan has keep major street already developed and change of density as well as building height. The result gets the ventilation performance on hot peak time is difficult. The ventilation potential estimated by using master plan land use as a land cover surface roughness and sky view factor. The study uses multiple suitability criteria of ventilation performance to estimate ventilation potential index. The southern part of the city ventilation slightly low. The ventilation potential index is 0.4 of new master plan proposal. Generally the new master plan proposal low ventilation performance.

## 4.2 Optimum Ventilation Design

The results are directly related to the criteria used design ventilation corridor and optimum density. According to the criteria use in table 8, from the criteria used for design ventilation corridor (40 %) land use, (10 %) terrain roughness, (30%) sky view factor and (20%) ventilation corridor buffer. According to Ren *et al.*, (2018) land use and sky view factor have given high priority for design ventilation corridor. From the land use water body, ponds, river and open space have given high grade for ventilation corridor design.

The final result of this study shows 0.8 ventilation potential index by decreasing roughness to 0.4 and optimum density of built environment 50%. This shows all city part can cool from Lake Tana breeze. The result shows this method is effective for city ventilation assessment.

## 5 Conclusion

Designing the city by considering passive cooling system is the main mechanism of reducing usage of high energy for cooling. The study explored investigating the paradoxes of density and Lake Tana’s Breeze of Bahir Dar city based on remote sensing (RS) and GIS technology. The present study mainly deals ventilation potential of city on prevailing wind on hot climate parameter.

The main ventilation source of Bahir Dar city have been studied from regional level to block level. The aim is to decide the density and source of natural ventilation for Bahir Dar city. The major ventilation corridor; Lake Tana, River Abay, Chockie Mountain at regional level as well as at city level. At high temperature season from February to May the fresh air flows from north to south. The analysis shows the maximum prevailing wind flows from north to south direction and the monsoon wind that flows from south west to north east.

The existing ventilation potential analysis shows the ventilation potential index is slightly high needs some intervention of buffer design. The ventilation performance of new structure plan proposal is relatively low and general because of proposing of high density built environment.

This study results investigating the ventilation potential of existing with ventilation potential index of 0.5 and design urban ventilation corridor with using GIS and remote (RS) of ventilation potential index of 0.4 and design the city based on the ventilation corridor design of 50% optimum density.

## 6 Recommendation

This study revealed the potential of passive cooling of Bahir Dar from the Lake Tana breeze. Based on the main finding of the study optimum ventilation potential corridor are identified and designed. The wind data for this study area collected from different international meteorological site. It is better to check farther by measuring the micro climate wind speed and direction for greater assurance.

Design and implementation of urban ventilation corridor design mainly related to master plan preparation proposal issues for sustainable city design. This study indicates how to design ventilation corridor in hot climate area cities. The ventilation corridor is not only as a ventilation but also used as public space.

Ethiopian city development agency must revises the planning approach according to the city location and micro climate data. Climate category of Ethiopian city and design standard preparation manual is needed. This study gives a relevant information how the design is changed from the physical planning philosophy.

Bahir Dar city Administration must consider the potential of Lake Tana city breeze and energy consumption for cooling, and revise the master plan concepts based on high ventilation performance of Bahir Dar.

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