Sustainable for All? How Satellite Remote Sensing Contributes to Sustainable Development in Africa and International Climate Policy

by

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Abstract

Satellite remote sensing applications are among the most important technological and data tools available to sustainable development practitioners today but are still underutilized. Sustainable development is multidimensional and characterized by many factors such as environmental sustainability, economic livelihoods, social dynamics, etc. – most of which satellites have a role in supporting. In this work, satellite contributions to the United Nations Sustainable Development Goals are robustly quantified using a novel impact classification method, and recommendations are given for key expansions of satellite remote sensing use in Africa from disease reduction of malaria and cholera, to implementation of social protection mechanisms for the poor at scale, to expansion of urban greenspace connectivity, and more. The domestic African satellite industry is also evaluated in the context of its capacity development and data policies. African satellite launches have grown significantly in recent years making up 62% of all 'rest of world' satellite launches in 2019 and with approximately 20 nations having established national space agencies through 2021. Small satellites, and nanosatellites in particular, have featured as many new entrant nations' debut satellites due to their modularity and utility. Room for improvements exist in increasing data usage and availability from successful missions, particularly with the new coordination capacities of the regional African Space Agency. Finally, blended data processing methods combining satellite environmental data and geospatial population data are used to illustrate water futures in East Africa. Predictive modeling and feature selection on the dataset were also able to detect El Niño effects in 2015 and connect rising heat levels and groundwater availability to climate-influenced micro-mobility patterns. This work highlights the importance of satellite data for serving small to medium-sized urban agglomerations in particular (<100,000), where the majority of Africa's urban population lives but are difficult to reach with in-situ methods. Policy recommendations are given in the context of the Paris Climate Agreement to integrate satellite data-based methods for realization of the Warsaw loss and damage mechanism and to spur implementation action to protect vulnerable nations and populations.

Thesis Supervisor: Sarah Williams
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I want to dedicate this thesis first and foremost to my mother. As is said in Islamic hadith, ‘Your mother, then your mother, then your mother’. Thank you three times over. You have taught me patience and grace and love and kindness and intelligence. I also want to dedicate this to my grandmothers. We stand on the shoulders of giants. Thank you for building a generation with the ability to discover, grow, inspire, live, love, and experience. To my brothers, cousins, family, thank you for loving and celebrating me for just being me.

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To my friends, you guys are amazing, and you already know it. Last but never least, thank you also to all the classmates, mentors, movers and shakers, teachers, and communities who I’ve come to know. You bring joy, and you inspire daily.

~ *For Amo Mohamed, Saleem, and Jaxson.* ~

P.S. A note to all those who will come after, strive higher. Be bigger and grander and better. I hope for all my wildest dreams to come true for you. I know you’ll make it happen.

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Glossary of Terms

EO	Earth Observation
SDGs	Sustainable Development Goals
UN	United Nations
AU	African Union
EU	European Union
RGB	Red, Green, Blue
SWIR	Short-wave Infrared
MWIR	Mid-wave Infrared
LWIR	Long-wave Infrared
LEO	Low Earth Orbit
MEO	Medium Earth Orbit
GSO	Geosynchronous Obit
GEO	Geostationary Orbit
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
ESA	European Space Agency

Chapter 1

Introduction

1.1 Overview

This thesis represents a holistic exploration of sustainable development aspects through the lens of technical instruments like satellite remote sensing and policy instruments like the Paris Climate Agreement. Sustainable development is a worldwide concern and a comprehensive way of describing and defining an improved livelihood for both people and Earth's natural system. A focus on the African continent is highlighted and many conclusions are specific to unique contexts in the region but can be expanded and generalized to many other similar regions or countries.

1.2 Main Research Question

Each section of this thesis asks, explores, and answers a distinct research question. The overarching guiding investigation is captured under the following:

> ***What is the effect of satellite remote sensing on sustainable development? And how can these effects be amplified and expanded using technology and policy tools?***

We will explore further sub-questions in each of the following sections.

1.3 Key Contributions

Key contributions from this study are made in several areas:

- Created a quantifiable and repeatable means of assessing the contributions of satellite remote sensing to sustainable development (and specifically the United Nations Sustainable Development Goals). This 'net impact score' is the first index of its kind formalizing the empirical relationship observed between the two.
- Identified key remote sensing applications to sustainable development issues in Africa by identifying thematic areas of the greatest promise in health, connectivity, agriculture and ecosystems, social protection, electrification, and city vital signs.
- Classified and comprehensively analyzed the domestic satellite industry, especially satellite activity, in African nations and found that much growth in satellite launches is being driven by nanosatellite proliferation and that more work will be needed from all nations in order to establish broad, coordinated Earth-observing missions and data-sharing policies between regions.

- Conducted a novel case study using remote sensing data in East Africa and was able to identify vulnerabilities to water futures at the city-level scale in several countries and also identify significant climatic factors influencing climate-related mobility patterns between cities in the region.
- Finally, suggested policy improvements in international climate policy stemming from the 2015 Paris Agreement by relating natural hazard exposure of nations to their respective contributions to overall climate warming and outlining key improvements to the Warsaw Loss & Damage Mechanism related to seasonal climate events and climate-forced migration and advocating for its speedy implementation.

1.4 Motivation

This study was motivated by a deep interest in sustainable development applications and outcomes and a desire to contribute a concrete and actionable thesis research project as a part of this important, growing landscape. My background in environmental engineering, satellite remote sensing, and technology and policy provided me with the ideal skillset to carry out this project. It is my hope that it will be used for fruitful purposes in the future.

1.5 Background

Sustainable development can be defined in numerous ways. Mostly throughout this thesis, it will be considered in the context of the United Nations Sustainable Development Goals (UN-SDGs) 2030, which are a set of 17 global points of progress agreed upon by the United Nations General Assembly member nations in 2015. These goals include broad aims such as 'No Poverty (SDG #1)', 'Zero Hunger (SDG #2), 'Good Health & Wellbeing (SDG #3)', 'Gender Equality (SDG #5)', 'Sustainable Cities & Communities (SDG 11)', 'Climate Action (SDG #13)', and 'Peace, Justice, & Strong Institutions (SDG #16)'. The Sustainable Development Goals include 169 further targets which provide more specificity on the goals. These are tracked using a set of 232 unique indicators for data replicability and standard measurement. The UN-SDGs were preceded by the Millennium Development Goals, which similarly included 8 goals primary for developing nations. Alternate sustainable development measures include the planetary bounds definition that describes and outlines a 'safe operating safe for humanity' first proposed in 2009.[i] Other regional definitions and plans have been established. This thesis will also consider the African Union's 50-year sustainable development plan known as the AU Agenda 2063.

Chapter 2

Sustainable Development Contributions (and Potential Contributions) of Satellites & Satellite-Enabled Technologies in Africa

2.1 Introduction

Many studies have established an empirical link between satellite remote sensing methods and the United Nations Sustainable Development Goals (UN-SDGs). The United Nations Office for Outer Space Affairs (UNOOSA) maintains a Space4SDGs repository establishing best practices for utilizing space technology in sustainable development applications. UN-SPIDER (The United Nations Platform for Space-based Information for Disaster Management and Emergency Response) was started in 2006 to address gaps for developing nations and build capacity towards disaster response and preparedness by synthesizing satellite data insights. Research has established strong links to sustainable development areas of resource management, water quality and quantity, monitoring of agriculture, city infrastructure health, climate change science, and more. Socioeconomic benefits of satellite earth observation (EO) missions have been well noted in the literature. Many researchers have drawn connections to the United Nations Sustainable Development Goals (UN-SDGs), however, the direct effects of satellite-enabled technologies have not been well quantified. Particularly at the current juncture when satellite activity in space is growing rapidly and many new commercial and governmental entrants are launching earth-observing, communications, and positioning missions, an in-depth understanding of sustainable development impacts is crucial.

2.2 Research Question

In this research section, I ask if it is possible to measure the magnitude of satellite earth observation's effect on sustainable development? The aim of this study is to quantify, categorize, and organize the magnitude of effects that satellite-enabled technologies have on sustainable development and the UN-SDGs. In other words, just how much do satellite platforms and their associated technologies contribute to each of the SDGs and how can spending on satellite technologies be best prioritized in the future?

2.3 Methodology

There are two methodologies presented in the context of this analysis. One is instructive in determining the relative impact of satellites on each of the SDGs and producing a quantitative index that can be used to prioritize and categorize sustainable development impacts. The second is a thematic analysis that explores and proposes specific policy developments for satellite usage expansion or new deployment that would have the greatest impact on sustainable development outcomes in Africa. A simplified graphic depiction of the methodological logic of each is presented in the figure below.

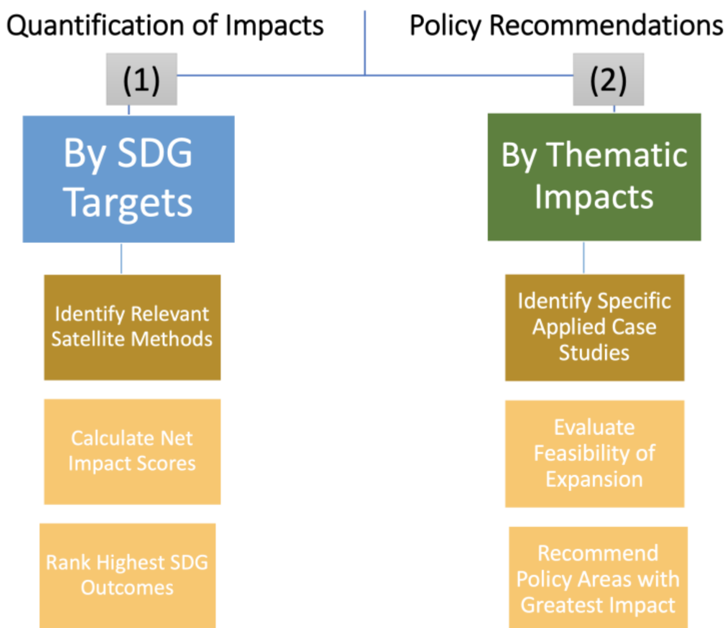


Figure 2-1: Methodological Logic for Sustainable Development Impacts

In order to do this, we first investigate the UN-SDGs at the level of 'SDG Targets'. The UN-SDGs are made up of 17 goals, 169 targets, and 232 indicators (some of which repeat in multiple goals). For each of the 169 SDG targets, they are assigned an effect category of 'direct', 'synergistic', 'measurement', or 'N/A'. This categorization signifies whether the SDG target is directly aided by a satellite technology, is synergistically aided by a satellite technology (i.e, has a complementary effect, though weaker than direct effect), or can simply be measured using satellites, respectively. They are also simultaneously classified by thematic impact area, which are broad categorizations that describe use-cases such as health, air pollution, land-use change, poverty mapping, weather prediction, road quality assessment, and disaster monitoring. Both categorizations are relevant for later methods to quantify impact of satellite technology on the SDGs.

Next, the relevant satellite methods identified in the previous step are further assigned an effect order. The effect order describes the level of satellite data processing and auxiliary data needed to arrive at the desired effect. In other words, it is a measure of technical feasibility and relevance of satellite methods. Here, first order effects are the ones most directly attained through a direct satellite product (one example is a false color image from a multi-spectral imager such as Landsat-8 OLI). Then, there are second order effects (satellite products attained through post-processing) such as a normalized difference water index (NDWI) map. Next, third order effects (a combination of satellite data with at least one other key data source) such as poverty mapping using VIIRS+DMSP night light imagery together with mobile phone and census data. After, there are fourth order effects (solutions that use a satellite platform-enabled technology) such as GPS tracking that enables wildlife tracking of endangered species subject to habitat degradation. Last, fifth order effects are the weakest in terms of primacy and are defined as a future potential development for satellite technology (one example would mass deployment of 5G protocols that enable vast expansion of IoT use-cases) or an institutional co-operation as a result of satellite activity (for example, formal or informal collaborations between space agencies and regional departments as part of satellite-enabled projects which lead to enhanced coordination efforts on both sides). First order effects are weighted the most strongly, whereas fifth order effects are weighted the least strongly. These are combined with values from the effect categories which were classified previously to create an index score.

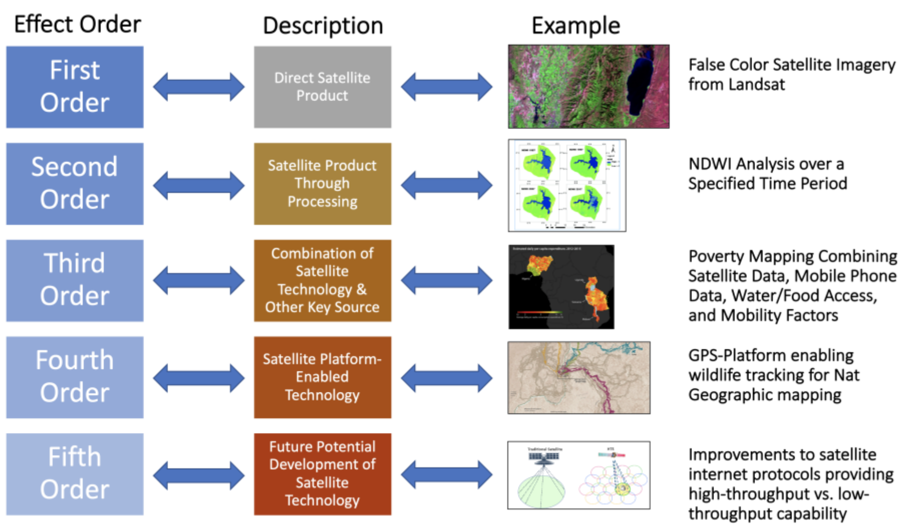


Figure 2-2: Effect Orders of Satellite Use Methods

Lastly, the effect orders are assigned to each SDG target as it corresponds to the methods used in the specific use-case. Each SGD target is allotted up to three relevant impacts, and these are classified as 'primary', 'secondary', and 'tertiary'. If the target is impacted by satellite technologies in three distinct ways, it will have effect order values for each of the three impact levels. SDG targets that are only relevantly impacted by satellite technologies in one way will only have an effect order value for the 'primary' impact level. The primary impact level is weighted the highest while a tertiary impact level is weighted the least. The full process diagram and the final anatomy of an SDG target classification are shown in the figures below.

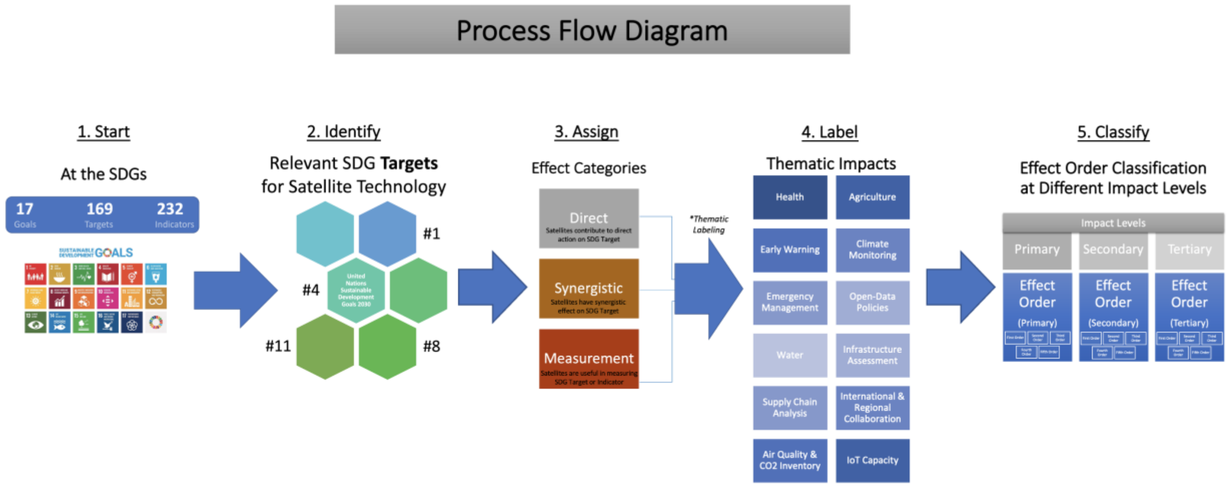


Figure 2-3: Process Flow Diagram of Full Classification Process

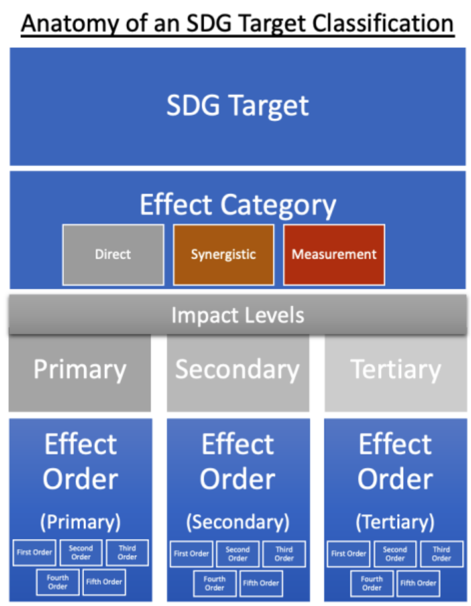


Figure 2-4: Close-up Anatomy of an SDG Target Classification

Each set of effect categories and effect orders are assigned a multiplier value from zero to one with one being the most impactful and zero being the least impactful. These values are used to create a “Net Impact Score’ index, also measured on a scale of zero to 1. A high net impact score means that the SDG target is strongly affected by a direct and high order satellite technology, possibly in more ways than one, once primary, secondary, and tertiary impact levels are taken into account. Thes multipliers and calculation methods are shown in the table below.

Multipliers for Effect Categories and Orders					
Direct	1	**First Order**	1	**Primary**	1
Synergistic	0.75	**Second Order**	0.8	**Secondary**	Residual of Primary / 2
Measurement	0.50	**Third Order**	0.6	**Tertiary**	Residual of Primary + Secondary / 3
N/A	0	**Fourth Order**	0.4		
		Fifth Order	0.2		

Table 2.1: Multipliers for Effect Categories and Orders

Further, the index of the "Net Impact Score' is derived according to the following equation:

Net Impact Score Equation:

$$Net\ Impact\ Score\ (1\ to\ 0)$$
$$= (Cat\ *\ Order) + \frac{((1-Cat*Order)*Order))}{2} + \frac{1-(Cat*Order)+\frac{((1-Cat*Order)*Order))}{2}}{3} * Order$$

Primary Secondary Tertiary

*Where **Cat** is the effect category (direct, synergistic, or measurement) and **Order** is the effect order (first, second, third, fourth, or fifth).*

This calculation method gives full weight to the primary impact level, while giving residual weights to both the secondary and tertiary impact levels, respectively. This serves as a methodology that prioritizes the impact levels in order of greatest importance. It is also done so that overall index values do not exceed one. If an SDG target at the primary impact level already has a net impact score of one (i.e. direct and first order), then the secondary and tertiary impact levels will have no effect on the score, as it is already maximized. However, if the net impact score at the primary impact level is 0.8 (i.e. direct and second order), then the remaining residual value of 0.2 can be marginally impacted by the scores of the secondary and tertiary levels. This helps build a robust system of measurement which can appropriately capture the multi-dimensionality that satellite-enabled technologies inherently exhibit.

It is important to note that effect orders were not repeated for the different impact levels. For example, if the primary way that an SGD target was impacted was through a second order effect (for example, agricultural cropland monitoring that was done using normalized difference vegetation index analysis, or NDVI) then the secondary impact level could not also be coded as a second order effect. Instead, it may be coded as fifth order effect, signifying the positive effect of international and regional cooperation around data cubes that are also used to monitor cropland during growing and harvest seasons.

This methodology is the first of its kind to comparatively quantify the real effect of satellite-enabled technologies on the SDGs. It is important in signifying to stakeholders and policymakers alike the inherent benefits of satellite technologies in a systematic way. The methodology can also be used to prioritize new satellite missions and to build partnerships and regional collaborations around data utilization for existing missions. In the next chapter, we will also discuss the emergence of new satellite nations, many of whom have stated goals around sustainable development but still lack robust means of quantifying these sustainable development aims. The following results here of this analysis reveal the SDG goals with the largest potential to benefit from satellite technology utilization. The interactions among the SDG goals are also taken into effect, as synergies and tradeoffs exist with the UN-SDG framework itself.
Finally, a deeper look into the thematic impact areas will be presented and will further link the most promising satellite application areas to the relevant, measurable SDG indicators which they have the potential to greatly accelerate (given uptake by nation-states and public and private partners). Suggestions for further investigations into related policy areas will be given.

2.4 Literature Review

A wide array of satellite technologies, platforms, and data processing methods were considered in the context of this study. The scope of these methods was determined through exhaustive literature review processes, conversations with domain experts, review of case studies and application instances, and experience of the author in the field. Knowledge of these methods was categorized and utilized for the classification methodology presented here and for attribution of satellite-enabled technological benefits to specific SDG targets and goals. The review of these technologies looked at the following aspects of interest, in particular: (1) Relevant satellite missions, (2) Satellite data processing methods, and (3) The role of new and emerging satellite technologies. The inclusion of the third parameter (new and emerging technologies) is relevant in part because the majority of the SDGs are specified until 2030 (some are set at the year 2020), and new technologies are likely to play a role in the achievement of the SDGs by the target date.

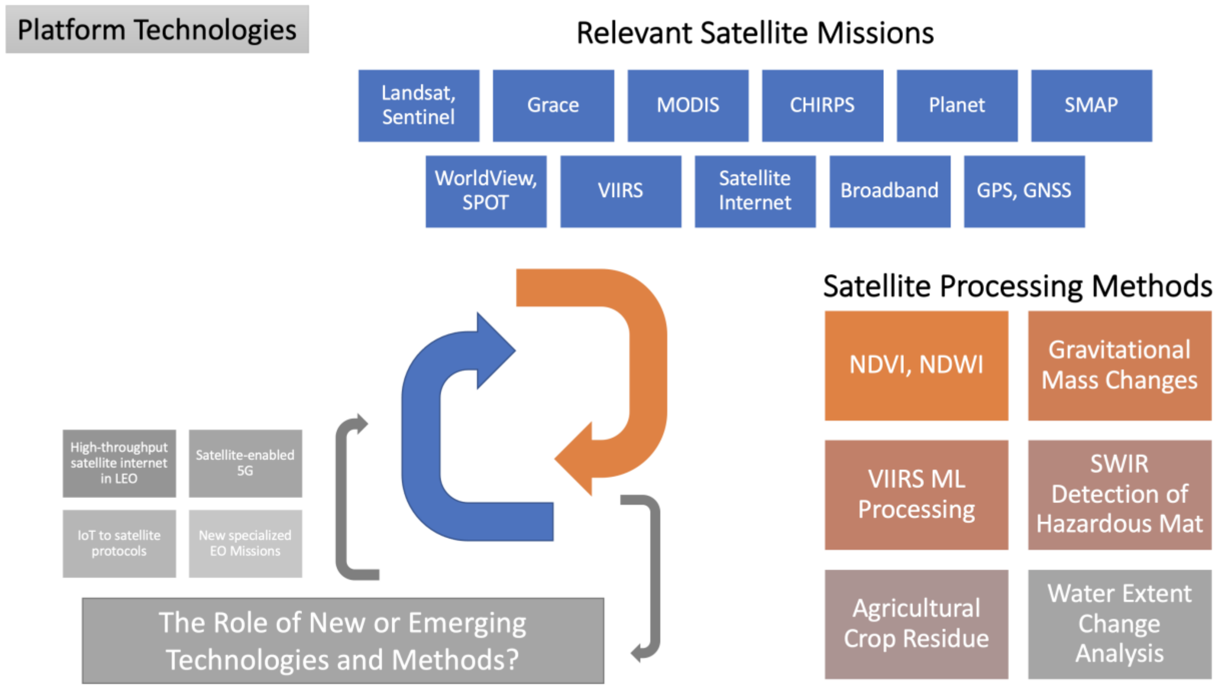


Figure 2-5: Satellite Platform Technology Ecosystem

Among the most ubiquitous earth-observing satellite technologies are coarse to medium resolution multi-spectral imagers such as the NASA Landsat series that have been collecting continuous EO data for the longest consecutive record dating back to the 1950s. Multispectral imagers collect imagery data in multiple electromagnetic bands beyond the visible RGB spectrum, often including near-infrared (NIR), shortwave infrared (SWIR), mediumwave infrared (MWIR), thermal, and panchromatic bands used for image sharpening in post-processing. The ESA's Sentinel satellites collect multi-spectral imagery data at a 10m resolution, higher than Landsat's 30m pixel resolution. Medium resolution imagers like Landsat and Sentinel have revisit times which allow for complete coverage of the Earth on average about every 8 days. MODIS and AVHRR multi-spectral instruments have much coarser spatial resolutions ranging from 250m – 1km but are able to provide complete pictures of the Earth system every 1-2 days. They are ideal for measuring large geographic areas with high frequency. Highest resolution imagery is provided by commercial satellite providers in B2B scenarios in most cases, and resolutions can be upwards of 50 cm like the WorldView satellites. Planetscope Labs operate a fleet constellation of CubeSats equipped with multi-spectral imagers that average 3m resolution in RGB and NIR bands which are appropriate for many uses such as vegetation indexes (NDVI) and surface water detection (NDWI).

Beyond imaging satellites, earth-observing missions are designed for many unique payloads and missions. TRMM (Tropical Rainfall Measuring Mission) and successor GPM (Global Precipitation Measurement) use radar and microwave imaging to measure precipitation. The SMAP (Soil Moisture Active Passive) mission makes use of active radar and passive sensing for insights on soil conditions. The NASA GRACE (Gravity Recovery and Climate Experiment) and GRACE-FO (GRACE Follow-On) satellites are novel missions which feature dual satellites capable of measuring gravitational changes to Earth mass and translating them to changes in terrestrial water storage and ice mass.[ii] VIIRS (Visible Infrared Imaging Radiometer Suite) night light data and DMSP-OLS (Defense Meteorological Satellite Program-Operational Linescan Sensor) nighttime images are popularly used as proxies for many insights like household income estimation intensity of industry activity on Earth. OCO-3 (Orbiting Carbon Observatory-3) is an instrument deployed aboard the ISS that detects carbon dioxide flux by detecting reflected sunlight intensity. The CYGNSS satellite constellation makes use of passive L-band GPS/GNSS signals to track hurricane wind speeds and image flood events.[iii]

Satellite remote sensing methods are very numerous and difficult to exhaustively list. Machine learning algorithms trained on night-light and visible imagery data have been able to predict household poverty levels with high accuracy. GRACE and GRACE-FO have revealed ice-sheet and groundwater storage change rates that were previously undetectable. Sentinel-2 data is suitable for monitoring algal blooms in coastal environments.[iv] ASTER data has been utilized to validate siltation levels due to dam operation.[v] SWIR bands are able to capture spectral variation to distinguish petrochemicals in soils.

Platform innovations make powerful contributions, as well. Cloud-based processing through Google Earth Engine has accelerated uptake for many end users by eliminating the need for local processing power or storage space. Many platforms host pre-processed satellite products that are ready for end use as-is, and this lowers a significant barrier to entry for practitioners of any background. Future and emerging innovations in satellite broadband internet deployment from LEO (low-Earth orbit) and possible 5G protocols also hold great promise for IoT connectivity.

2.5 Results of Ranking by SDG Targets

2.5.1 Categorization of Satellite Impacts on SDGs

After categorization of each of the 169 SDG targets by effect category and thematic impact area, several interesting trends emerged. For the SDG targets, satellites were found to have a ‘direct effect’ on 39 targets. Satellites were found to have a ‘synergistic effect’ on another 61 SDG targets. Satellites were also found to have a ‘measurement’ effect on another 25 SDG targets. In total, satellites and satellite-enabled technologies are found to be relevant to 122 of the 169 UN-SDG targets. This is a 72% relevance in absolute terms without taking into account synergies and tradeoffs that exist between different SDG goals.

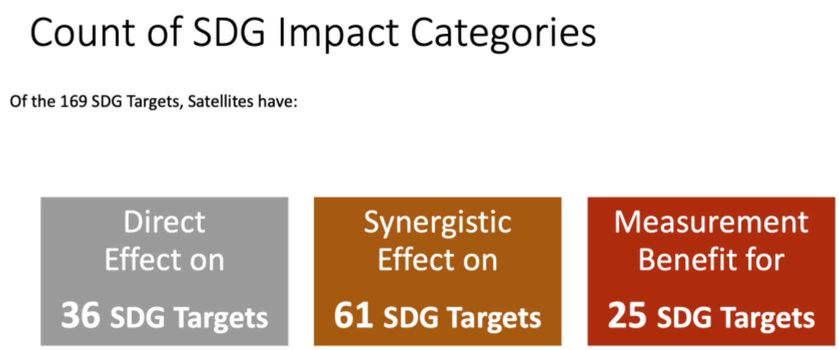
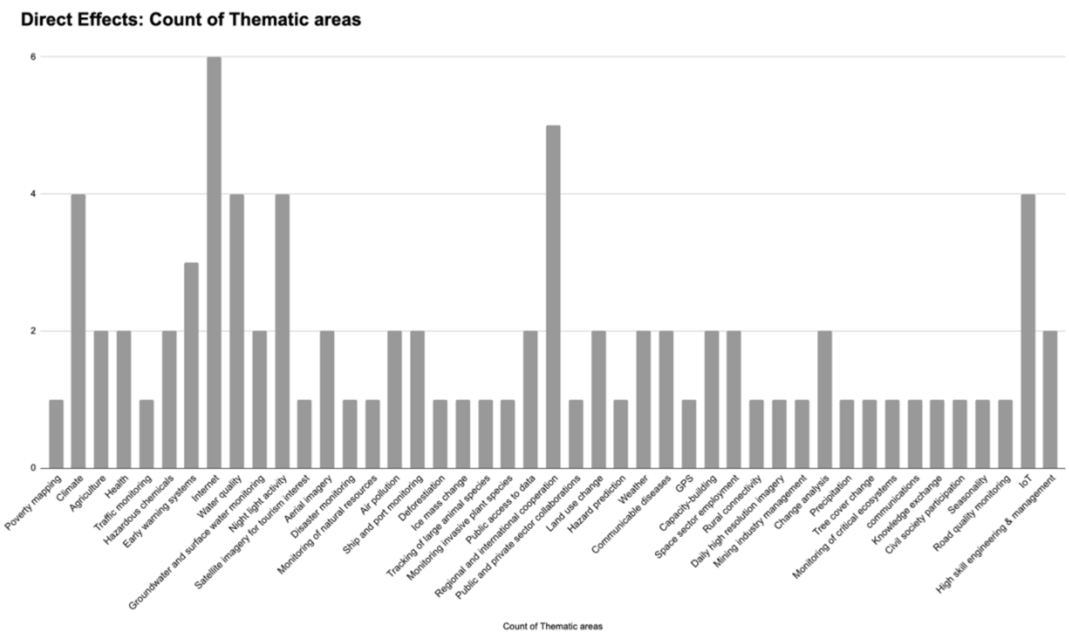


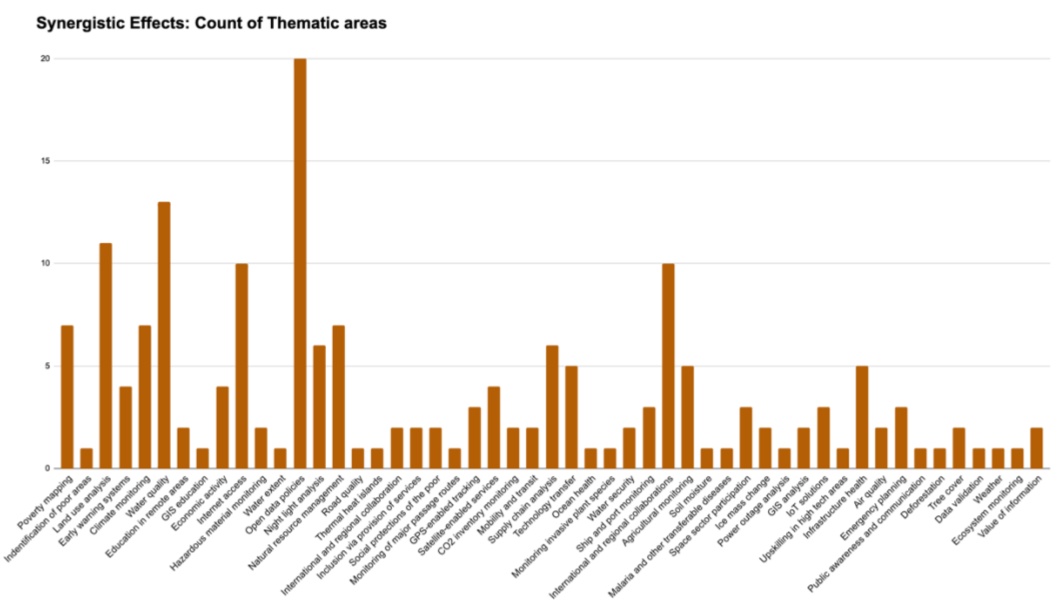
Figure 2-6: Count of SDG Impact Categories

Direct effects were found for SDG targets within the following SDG goals: #1 (No Poverty), #2 (Zero Hunger), #3 (Good Health & Well-Being), #4 (Quality Education), #6 (Clean Water & Sanitation), #8 (Decent Work & Economic Growth), #9 (Industry, Innovation, and Infrastructure), #11 (Sustainable Cities & Communities), #12 (Responsible Consumption & Production), #13 (Climate Action), #14 (Life Below Water), #15 (Life On Land), #16 (Peace, Justice & Strong Institutions), and #17 (Partnerships for the Goals). Synergistic effects had by satellites were found in SDG targets in each of the 17 goals. In particular, this highlights the large positive externalities of satellite-enabled technologies that is often difficult to measure through traditional means. Measurement effects were found for SDG targets within goals #1 (No Poverty), #2 (Zero Hunger), #4 (Quality Education), #5 (Gender Equality), #6 (Clean Water & Sanitation), #7 (Affordable & Clean Energy), #8 (Decent Work & Economic Growth), #9 (Industry, Innovation, & Infrastructure), #11 (Sustainable Cities & Communities), #12 (Responsible Consumption & Production), #13 (Climate Action), #15 (Life on Land), #16 (Peace, Justice, & Strong Institutions), and #17 (Partnerships for the Goals).

2.5.2 Classification of Thematic Impact Areas

In addition, a count of thematic impact area labels was undertaken. This was disaggregated by effect categories. Direct, synergistic, and measurement effect categories each exhibited varying thematic trends. Theme classifications with the highest frequency included ‘internet’, ‘regional and international collaborations’, ‘water quality’, ‘night light activity’, and ‘early warning systems’. Other areas which were also significant included ‘agriculture’, ‘health’, ‘groundwater and surface water, ‘ship and port monitoring’, ‘land-use change’, and more. For synergistic effects, the highest frequency thematic area was ‘open data policies’ followed by ‘water quality’, ‘land-use analysis’, ‘international and regional collaborations’, ‘internet access’, and ‘natural resource management’. The remaining synergistic effects were more evenly spread with a wide distribution across multiple thematic areas including ‘poverty mapping’, ‘climate monitoring’, ‘supply chain analysis’, ‘technology transfer’, ‘infrastructure health’, and more. Thematic impact areas for the measure effect category were most concentrated around nodes which included many of the previous thematic areas such as ‘land-use change’, ‘international and regional collaboration’, ‘climate’, ‘open data policies’, ‘agricultural monitoring’, and ‘infrastructure health’. The value of open data policies and international collaborations in particular is critical. This helps public and private stakeholders from diverse backgrounds to access the wealth of information and secondary services that are built upon satellite systems. NASA’s Earth Science Data Systems (ESDS) Program has provided open data access to earth-overserving (EO) satellite data since 1994 with limited restrictions for use. The European Space Agency (ESA) also maintains a similar open data policy which provides free data from Sentinel, Envisat, and other missions.





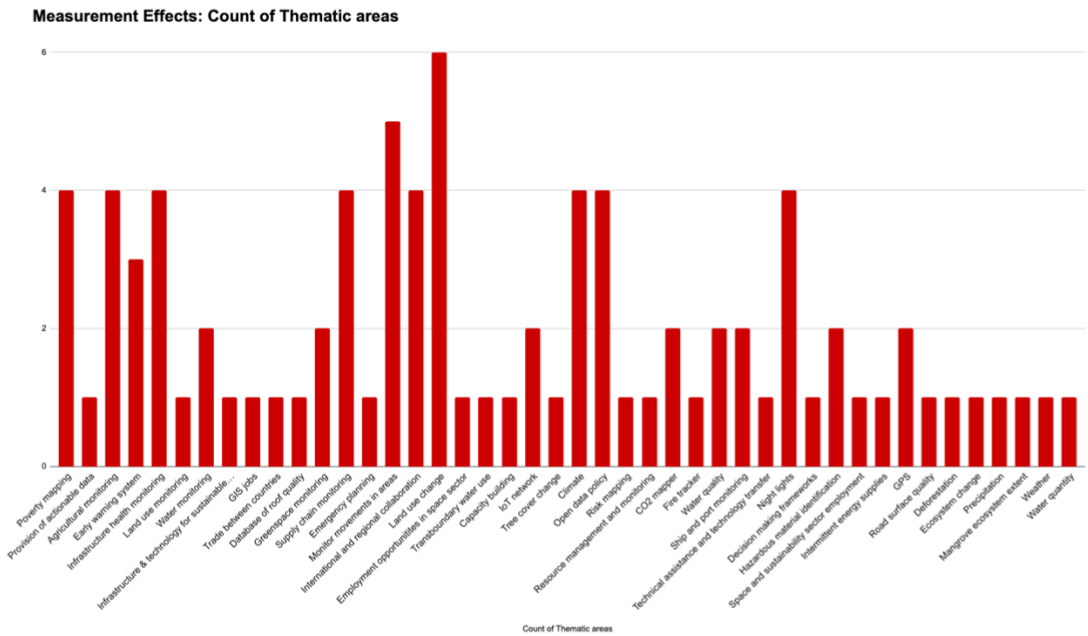


Figure 2-7: Count of Thematic Areas by Direct, Synergistic, and Measurement Categories

Following the classification process, the net impact score was tabulated iteratively according to the ‘Net Impact Score’ equation for each row of the SDG targets. Scores are reported cumulatively by impact level, i.e., the secondary net effect scores include the primary net effect score value. Therefore, tertiary net effect scores are also the cumulative total net impact score for each SDG target as they include the sum of the primary and secondary score values.

2.5.3 Calculation of Satellite Impacts at SDG Target Level

When visualizing a histogram of net impact scores, looking only at the primary effect scores, we observe a skewed effect towards lower values in the range of approximately 0.10 to 0.45, with sparse scores in the upper ranges. This would indicate a relatively weaker overall effect of satellites on SDG targets.

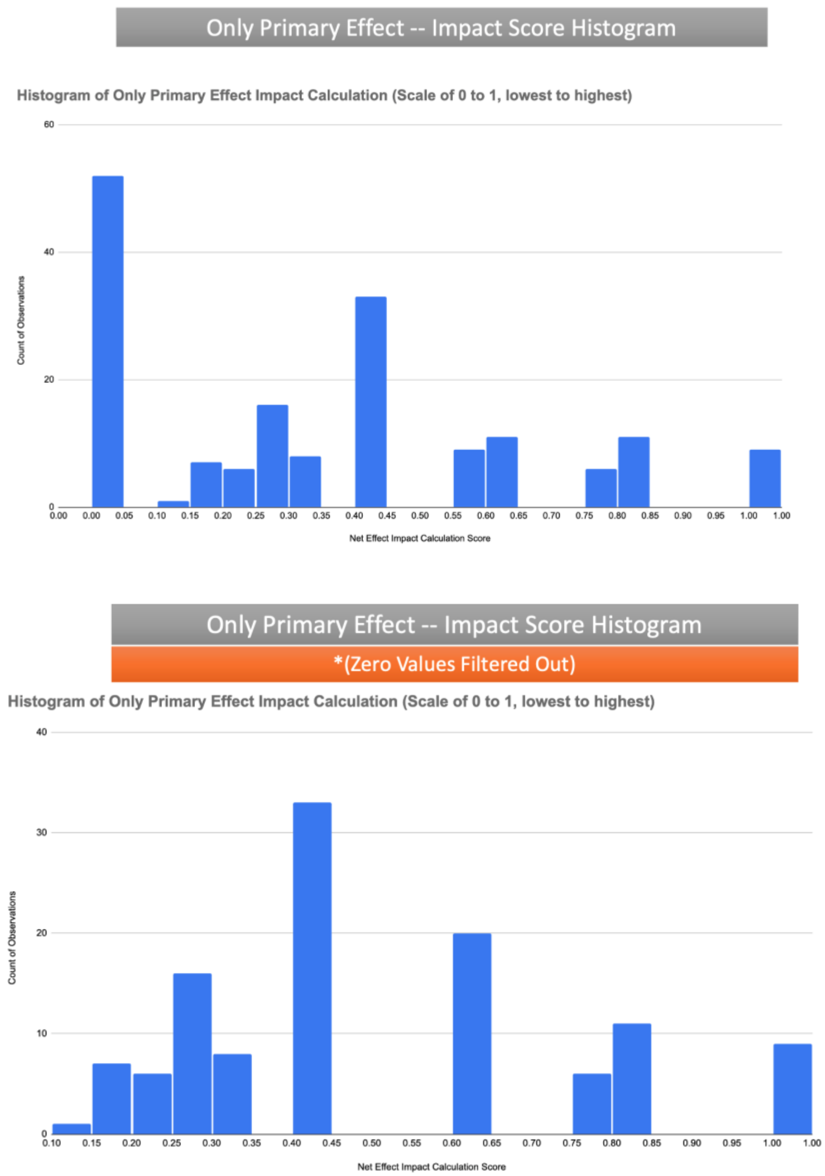


Figure 2-8: Histograms of 'Primary' Effect Scores

However, when the full cumulative effect is taken into account (totaling primary, secondary, and tertiary impact scores), we observe a fuller range of values filling out the mid and upper-ranges of the index distribution. The majority of values here fall between 0.35 to 0.60 and between 0.70 to 0.90. Here, the total observed effect is much higher when compared to the primary effect only. It is reasonable to conclude that satellites and satellite-enabled technologies contribute to SDG target advancement in more than one way most often, and this dichotomy is important to capture when dealing with complex human and environmental systems. Values of 1 on the net impact scale are generally associated with satellite internet provision, especially in remote areas which previously had no connectivity. A full discussion of the satellite technologies and processing methods considered in the above index classification will be addressed in a following section.

Figure 2-9: Histograms of 'Cumulative' Effect Scores

2.5.4 Ranking of Satellite Impacts on SDG Targets

Ordering the SDG targets by highest cumulative net impact score, we see many targets associated with SDG #4 (Quality Education) in the top rankings, mainly attributed to contributions of satellite internet access in rural and remote areas. In addition, climate and water-related SDG targets in SDG Goal #6 (Clean Water & Sanitation), #13 (Climate Action), #14 (Life Below Water), and #15 (Life on Land) are well represented. They relate to a myriad of issues such as water quality and efficient use, marine pollution, ocean acidification, desertification, ecosystem health (mountains, forests, terrestrial, marine, and freshwater), and biodiversity. Earth-observing (EO) satellite missions play a large role in monitoring and often protecting the overall health of the Earth system by providing holistic snapshots of vital indicators at continuous and near-real time scales over large geographic swaths. Other notable SDG targets include 1.5 which describes resilience of the poor, 2.4 which describes sustainable food production systems, and 13.1 which describes adaptive capacity to natural disasters. Many of the key contributions of satellite-enabled platforms are through the provision or support of social protection systems that are data-driven. These systems can be pre-emptive, such as early warning systems for famine risk level or tropical disease outbreaks like malaria and Rift Valley fever. They can also be restorative such as basic income programs or emergency financial support to vulnerable populations through high-fidelity poverty mapping based in part on satellite data inputs. Togo's Novissi program was a fully digital cash-transfer assistance program enacted between 2020 and 2021 to provide emergency relief to informal sector workers and low-income Togolese citizens affect by the COVID-19 global pandemic. First iterations of the program were broad in targeting, whereas following implementation used satellite night light data in tandem with mobile phone data and other big data sources to identify the poorest regional areas in Togo (approximately 200 cantons) and further prioritize the most vulnerable neighborhoods and households.[vi] Further SDG targets with high ranking scores relate to a number of areas: (1) Sustainable communities and infrastructure, identifying issues like 11.4, cultural and natural heritage landmark preservation; 3.6, road traffic accidents and deaths; 10.7, safe migration of people; and 12.a, sustainable consumption. (2) Health and wellness, with targets such as 3.9, illness from hazardous chemicals; 3.2, preventable deaths of newborns (namely from communicable diseases); 3.3, communicable disease deaths; and 3.d (health early warning systems). (3) Statistical capacity and international cooperation though SDG 17.18, capacity-building support to developing nations and 17.19, statistical capacity and alternative measures to GDP.

In the next section, we will explore policy areas centered around many of the key identified SDG targets. They are grouped broadly by category of thematic impact:

- Climate
- Internet & Connectivity
- Pollution & Waste
- Social Protection
- Health & Wellness
- Hazard Resilience
- City Health & Mobility
- Natural Resources
- Statistical Capacity
- Co-operation & Capacity Building
- Technical Innovation

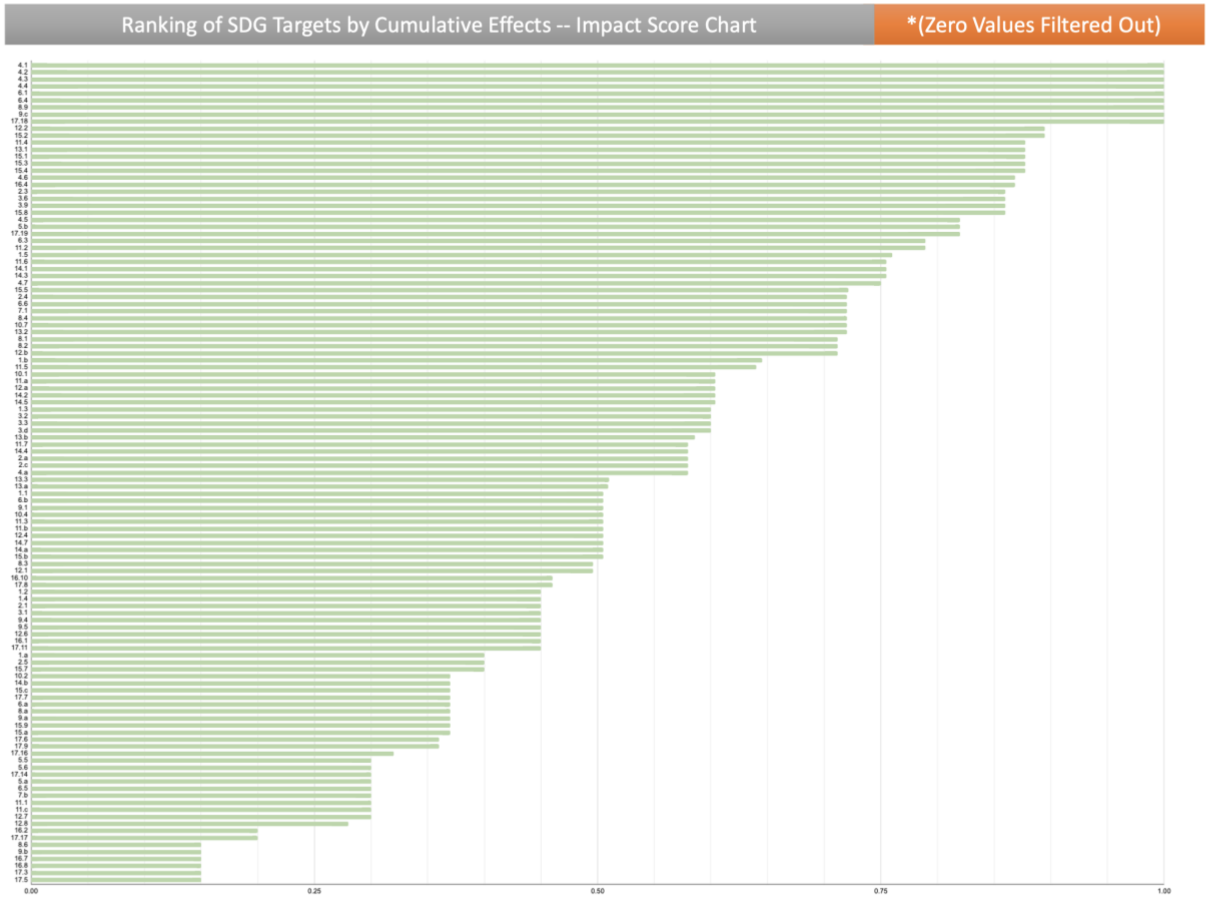


Figure 2-10: Ranking of SDG Targets by Cumulative Effect Scores

2.5.5 Ranking of Satellite Impacts on SDGs (17 Goals)

Next, after reaggregating net impact scores back from the level of SDG targets to the level of SDG goals, we are able to see the broad impacts on the UN-SDGs more clearly. Results are displayed by aggregate net impact score for each of the 17 goals. The zero values are filtered out to exclude targets which were not considered in the analysis. Adjusted aggregate total effect are recalculated to accurately reflect the mean value for each SDG.

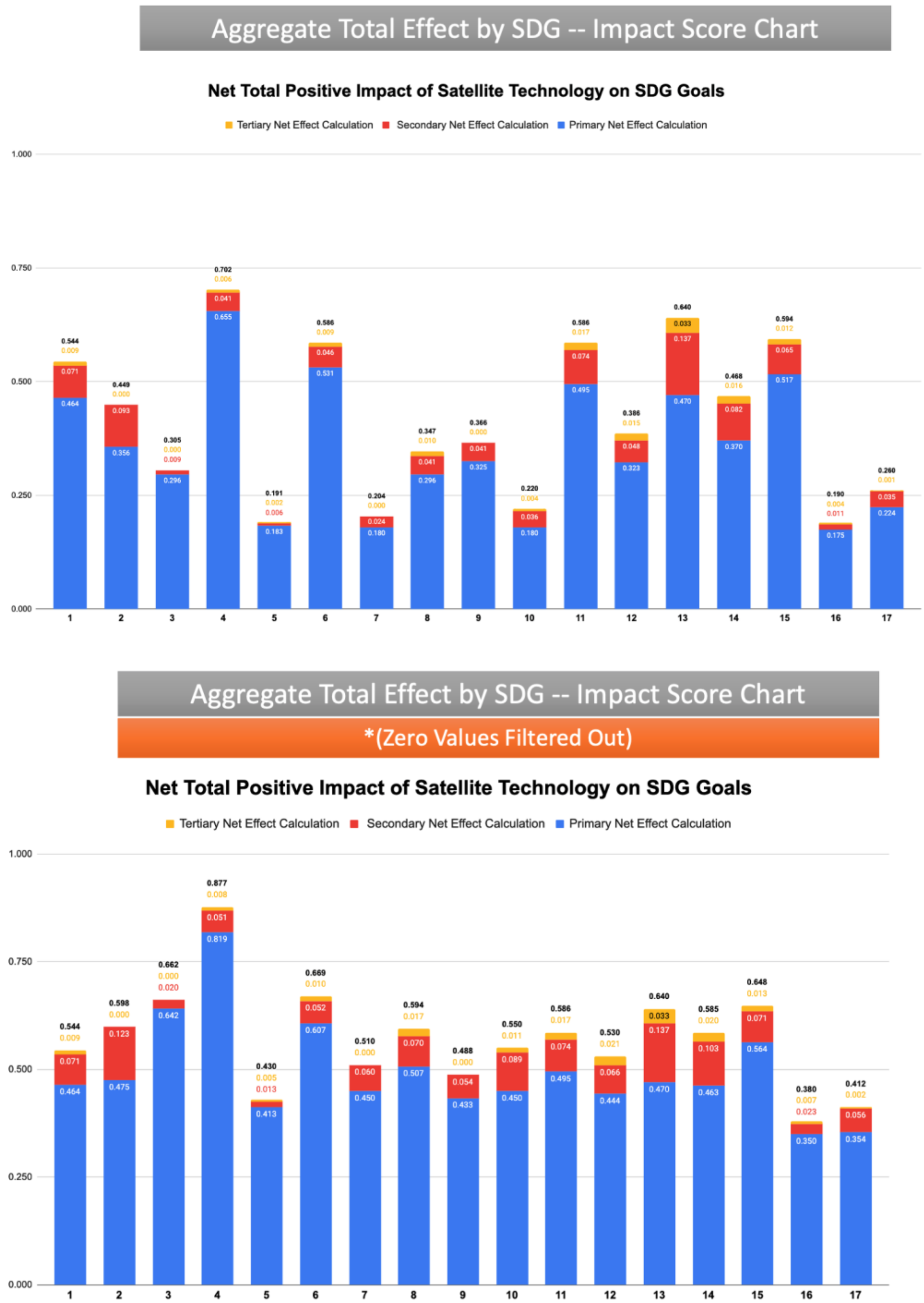


Figure 2-11: Impact Scores of SDGs

Finally, the ranking of SDGs reveals the highest impact score for SDG #4 (Quality Education), followed by SDG #6 (Clean Water & Sanitation), #3 (Good Health & Wellbeing), #15 (Life on Land), #13 (Climate Action), and #2 (Zero Hunger).

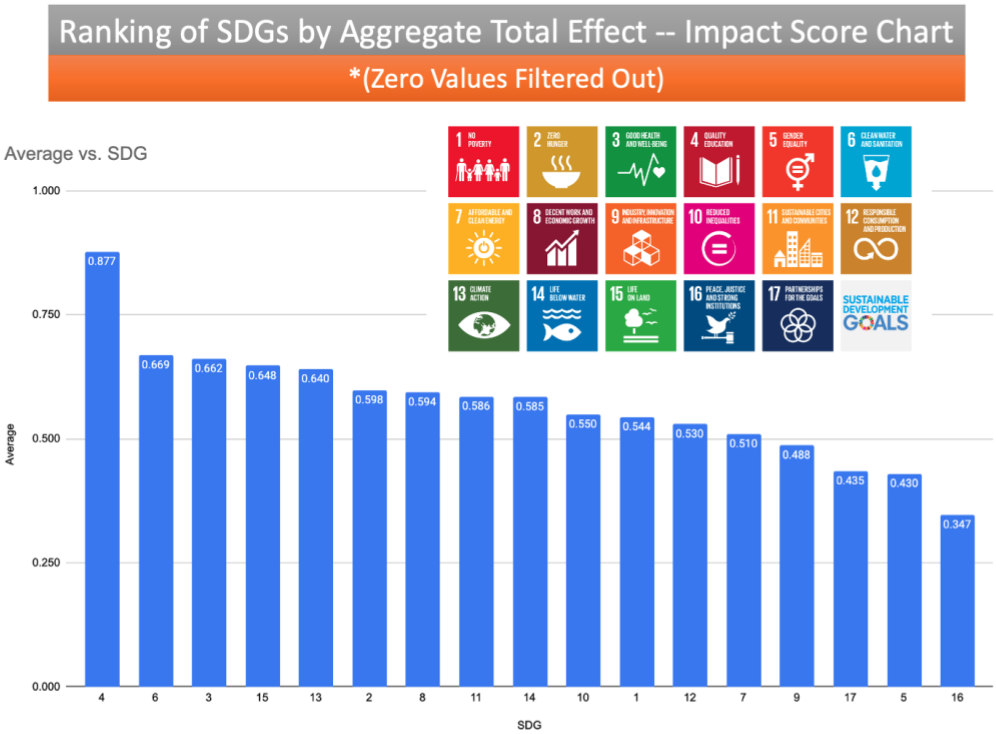


Figure 2-12: Ranking of SDG Impact Scores

Ranking of SDGs by Aggregate Total Effect -- Impact Score Table

*(Zero Values Filtered Out)

SDG Goal	Description	Average
4	Quality Education	0.877
6	Clean Water & Sanitation	0.669
3	Good Health & Wellbeing	0.662
15	Life On Land	0.648
13	Climate Action	0.640
2	Zero Hunger	0.598
8	Decent Work & Economic Growth	0.594
11	Sustainable Cities & Communities	0.586
14	Life Below Water	0.585
10	Reduced Inequalities	0.550
1	No Poverty	0.544
12	Responsible Consumption & Production	0.530
7	Affordable & Clean Energy	0.510
9	Industry, Innovation, and Infrastructure	0.488
17	Partnerships for the Goals	0.435
5	Gender Equality	0.430
16	Peace, Justice, & Strong Institutions	0.347

Table 2.2: Ranking of SDG Impact Scores

2.5.6 Synergies and Tradeoffs Among Sustainable Development Goals

In order to account for interactions among the SDGs, the results reported by Pham-Truffert et. al. were interpreted to attain negative and positive interaction aggregate values for each SDG.[vii] These were resolved as percentage values for the share of total interaction values. Some SDGs have outsize interaction effects as compared to other goals. Goal #7 (Affordable & Clean Energy) has both significant positive and negative interaction outcomes. Goal #6 (Clean Water & Sanitation) is notably high in the share of positive interactions. Goal #2 (Zero Hunger) is similarly observed to have many positive and negative interaction values.

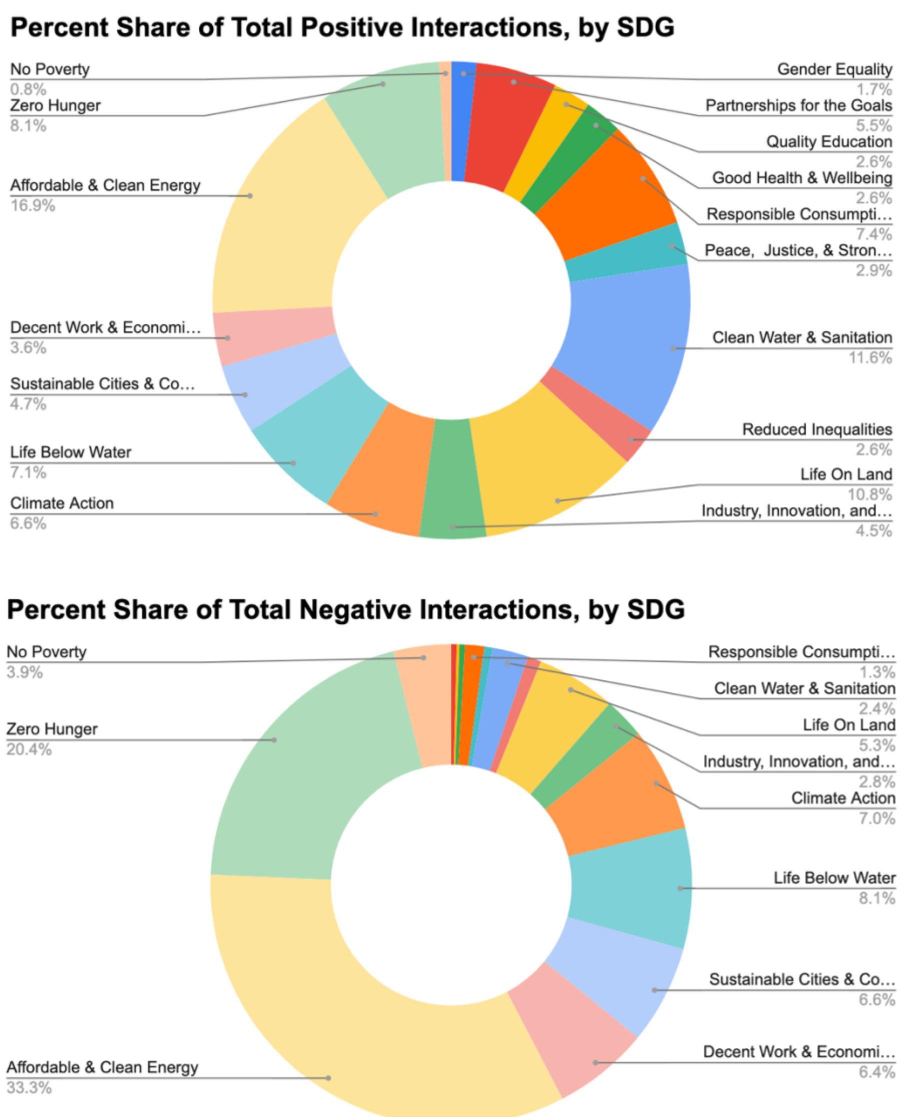


Figure 2-13: SDG Percent Share Negative/Positive Interactions

After weighting the ratio of positive and negative interactions for each SDG individually, it can be seen that some SDGs have much more synergistic or neutral interaction effects than others. SDG #5 (Gender Equality) was not found to have any negative interaction points with other SDGs. The majority of SDGs have overwhelmingly positive interactions. SDGs #1 (No Poverty), #2 (Zero Hunger), and #7 (Affordable & Clean Energy) exhibit notable tradeoff qualities with other SDGs, namely climate and sustainability-related SDGs.

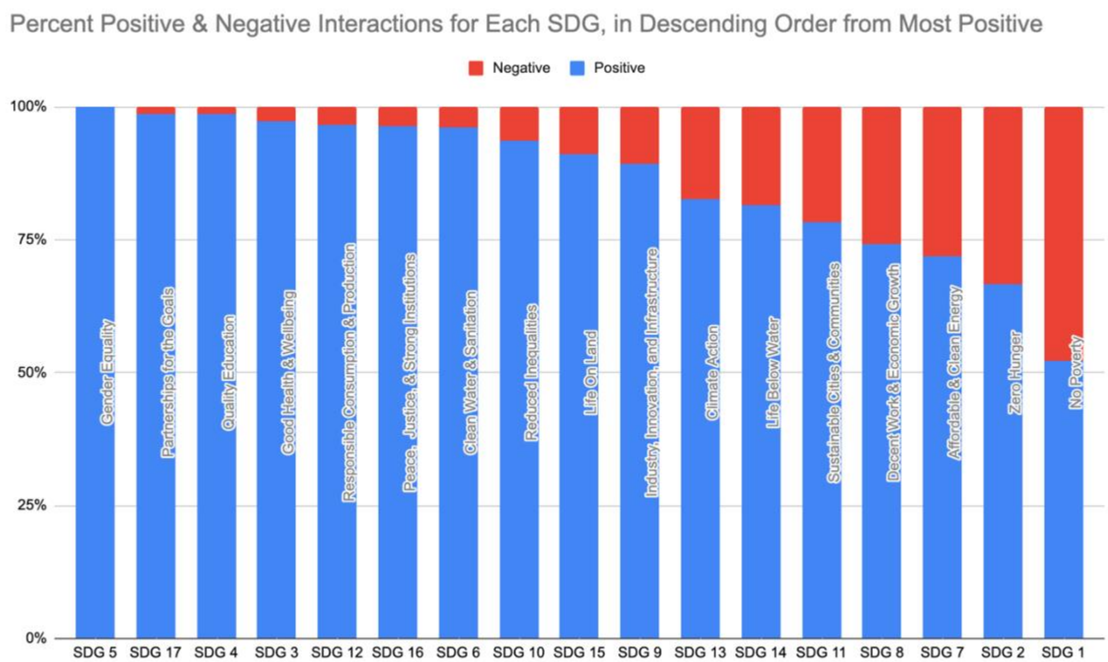


Figure 2-14: SDG Ratios of Negative/Positive Interactions

The percent of positive interactions from among the total amount of interactions was used as a weighting value. This ratio value for each SDG was multiplied by the cumulative aggregate impact scores attained in the step above. This additional step gives the weighted value of the net impact score which considers the inherent competing nature of many of the SDG indicators and concurrent goals. As such, all weighted impact scores are less than or equal to the cumulative impact score computed in the previous step. A simplified graphic of the method is displayed below.

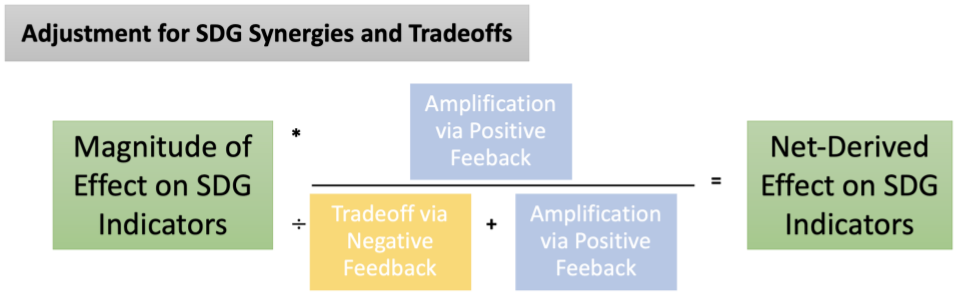


Figure 2-15: Visualization of Adjustment for SDG Synergies and Tradeoffs

2.5.7 Weighted Ranking of Satellite Impacts on SDGs (17 Goals)

The adjusted values had an observable altering effect on the outcome of the ranking process. Several SDGs assumed a different positioning after the interaction adjustment was applied. This is an interesting finding, as it indicates that compound benefits are worth carefully studying when considering a specific sustainable development outcome. The amplifying synergy that is exhibited by a number of goals is enough to make a significant change in the overall efficacy of certain sustainable development strategies. Also, the tradeoff effects are not insignificant in relation to many of the SDGs of interest. This is of critical importance to policymakers, satellite engineers and data-users alike. Further work should be done to isolate these intra-SDG effects at the granular level of SDG indicators, of which there are 232 in total.

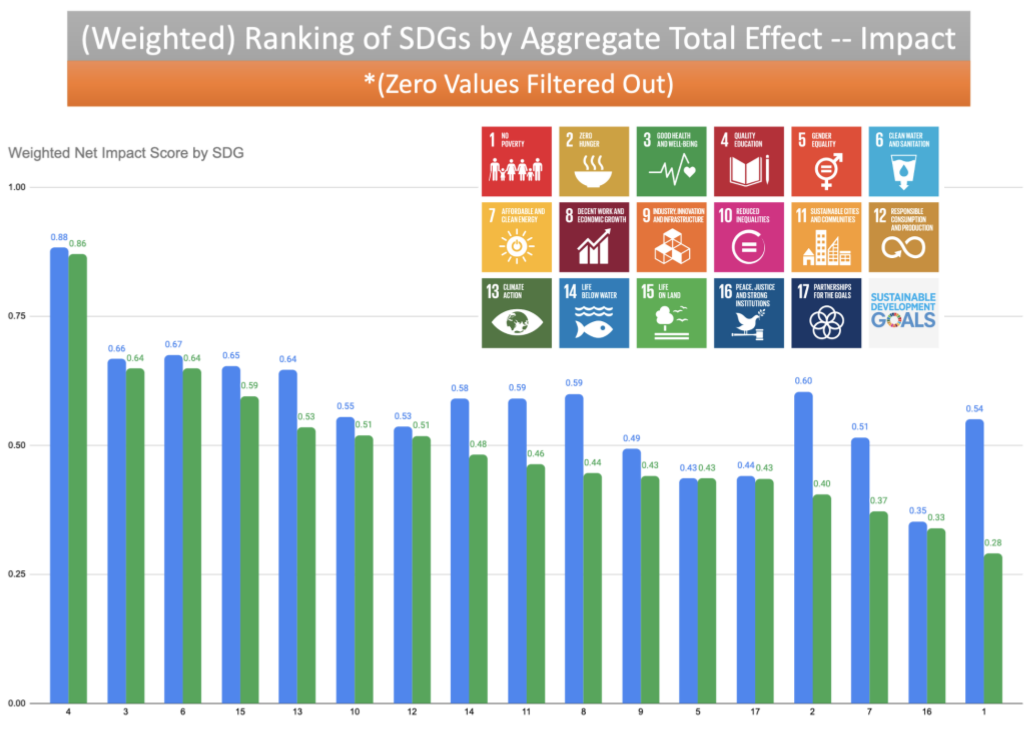


Figure 2-16: Weighted Ranking of SDG Impact Scores

As corresponds to their percent interaction scores derived in the previous step, SDGs #1 (N Poverty), #2 (Zero Hunger), and #7 (Affordable & Clean Energy) had the largest decreases in their weighted aggregate impact score. Still, advances in these sustainable development areas are critical and overall very relevant to satellite methods, but careful consideration should be given to balance the complex sustainable development landscape simultaneously. The table below gives full average and weighted average values of net impact scores. Rows coded as green indicate that the SDG moved upwards in the ranking process after interaction effects were applied. Red rows indicate that the SDG moved downwards in the ranking after the process. Blue values are of rows that remained the same as their previous ranking. Only three goals remained unchanged in overall positioning (#4- Quality Education, #15 – Life on Land, and #13 – Climate Action). Other goals moved by a number of positions, such as #10 (Reduced Inequalities) which climbed by four ranking spots and #8 (Decent Work & Economic Growth) which fell by three spots in the overall ranking.

(Weighted by Positive Interaction Level) Ranking of SDGs by Aggregate Total Effect -- Impact Score Table

*(Zero Values Filtered Out)

SDG Goal	Description	Average	Weighted Average
4	Quality Education	0.88	**0.86**
3	Good Health & Wellbeing	0.66	**0.64**
6	Clean Water & Sanitation	0.67	**0.64**
15	Life On Land	0.65	**0.59**
13	Climate Action	0.64	**0.53**
10	Reduced Inequalities	0.55	**0.51**
12	Responsible Consumption & Production	0.53	**0.51**
14	Life Below Water	0.58	**0.48**
11	Sustainable Cities & Communities	0.59	**0.46**
8	Decent Work & Economic Growth	0.59	**0.44**
9	Industry, Innovation, and Infrastructure	0.49	**0.43**
5	Gender Equality	0.43	**0.43**
17	Partnerships for the Goals	0.44	**0.43**
2	Zero Hunger	0.60	**0.40**
7	Affordable & Clean Energy	0.51	**0.37**
16	Peace, Justice, & Strong Institutions	0.35	**0.33**
1	No Poverty	0.54	**0.28**

Table 2.3: Weighted Ranking of SDG Impact Scores

Outcomes from this methodology produced useful, informative, and quantifiable results as to the efficacy of satellites in achieving the SDGs, as well as the specific relative ease or friction involved in deploying those same satellite methods. The resulting rankings provide evidence-based justification and calculation steps to determine net impact in each sustainable development area. This index can be used in future studies to review satellite sector activity, to make progressive policy that prioritize sustainable development outcomes through peaceful uses of space, and to help in planning and justification of future satellite missions and emerging space nations. The process is also repeatable through the classification steps and guidelines presented above. Additionally, it can be used selectively to compare a handful of SDGs (or other means of defining sustainable development areas) directly to each other in order to best plan for successful mission outcomes.

Another key area of application will be in the development of further data-sharing policies and protocols which extend beyond current levels and agreements. A significant amount of satellite data still remains inaccessible to researchers and practitioners for regular use. This greatly limits the ultimate deployment of useful satellite methods at scale and at point-location use. Many emerging space nations have also begun launching new national satellites and hyper-specific mission payloads, but much of this data is not covered by any open-data sharing policy at all. This paradigm shift is imperative to have effective use of satellite-enabled technologies for sustainable development by end users. Lastly, processing barriers to utilizing satellite data for useful insights remain a significant challenge. Advances in cloud-storage and processing platforms like Google Earth Engine have made non-trivial strides in increasing usage and accessibility.[viii] [ix] However, it still remains that domain knowledge and satellite data processing familiarity are often required for robust ability to generate insights and update results on a frequent basis.

The net impact scoring classification creates a compelling body of evidence and prioritization mechanism for quantification of satellite remote sensing impacts on sustainable development. The top SDG targets by rankings embody a host of different sustainable development needs. Moving beyond classification, the next section of the study presents actionable recommendations for expanding and introducing new satellite application capabilities that concretely advance the SDGs.

2.6 Policy Recommendations of Remote Sensing Expansion in Africa by Thematic Impact Areas

Six areas of thematic impact have been identified as priorities for advancing sustainable development significantly using satellite capabilities. The study identified impacts in the thematic areas of **health, agriculture, electrification, city vital signs, social protection, and internet connectivity.** Water was also identified, which we explore in a later section. The relevant methods are described in detail, and estimates of potential impact are presented. In particular, successful case studies have been used to model proposed expansion of practices for other similar contexts. These proposed policy expansions are then quantified using the SDG targets, showing how satellite remote sensing can concretely be utilized to achieve the SDGs by their target years given that appropriate, timely action is taken. These recommendations are strongly encouraged to be adopted by policymakers and decision makers in the public and private sectors of nation-states.

2.6.1 Health and Wellness

2.6.1.a Reducing Endemic Communicable Disease Outbreaks with Lead-Time Prediction

- **Relevant SDG Targets**
  (SDG 3.3) (SDG 3.4) (SDG 3.8) (SDG 3.d)

In the area of health, reduction of communicable and tropical disease outbreaks is the target of interest. Early warning systems and proofs of concepts have been developed, and deployed in some cases, for predicting outbreaks of communicable diseases. These include malaria, cholera, chikungunya, dengue, and Rift Valley Fever. Particularly for monitoring of vector-borne diseases, environmental precursor variables and leading indicators derived from satellites have a high success rate in predicting outbreaks. A 2018 study concluded that rainfall seasons are likely casual with cholera epidemic waves in Yemen.[x] It has also been found that El Niño weather events trigger Rift Valley fever in eastern Africa, while La Niña has the same effect in southern Africa.[xi] Methodology developed to address Rift Valley Fever outbreak in Senegal relies mainly upon precipitation data from the TRMM (Tropical Rainfall Measuring Mission) along with high resolution imagery from Quick-Bird commercial satellites to identify vector hosts (such as cattle), resulting in a precise and low-data volume conceptual approach for vector-borne disease prediction.[xii] Numerous studies verify the technical feasibility of detection of endemic malaria spread months in advance using optical sensors, radiometric measurements of soil moisture, precipitation radars, and digital elevation data from satellites.[xiii] Examples of successful use scenarios have been carried out in diverse contexts: The Gambia, India, Ethiopia, and Kenya, for example.[xiv] [xv] [xvi] [xvii] Technical feasibility has advanced significantly in recent years to deployable levels. Human factors in prediction and capacity-building for successful resource deployment remain critical dependencies for effective mass use.[xviii] This study proposes the expansion of these methodological approaches for vast advancement of communicable disease reduction in adults and children as follows:

Health Policy Recommendation #1: Malaria Reduction

- Utilize 1-month lead time prediction capabilities to prevent endemic malaria outbreaks in communities before infection and to staff hospitals before probable waves
- This method has been validated in a rural hospital in Kenya and requires only satellite rainfall data, average temperature, and evapotranspiration.[xix]
- Malaria is most prevalent in Sub-Saharan Africa today. Early warning with 1-month lead time together with increased capacity for health worker deployment and supplies can effectively half malaria rates by 2030 (SDG 3.3. & SDG 3.4).

Health Policy Recommendation #2: Cholera Prevention

- Use 6-month seasonal lead time insights from GRACE terrestrial water storage variations to predict seasonal above-average cholera rates well in advance[xx]
- Given large time scale, apply long-term strategies to improve water sanitation and filtration in high-risk areas
- Use 1-month lead time, region specific models for cholera epidemic prediction and apply acute standardized response strategies (requires some additonal demographic and economic data)[xxi]

- Highest at-risk population for endemic cholera is also Sub-Saharan Africa.[xxii] Action on endemic prevention would have cumulative effects, as populations with improved sanitation are less susceptible in following years, as well. Approximately 40% reduction could be seen by 2030.

2.6.2 Food, Agriculture, and Ecosystems

2.6.2.a Proactively Reward Sustainable Agriculture and Ecosystem Management Through Automated Monitoring Programs

- **Relevant SDG Targets**
  (SDG 2.c) (SDG 2.3) (SDG 2.4)
  (SDG 15.1) (SDG 15.2) (SDG 15.3)

A number of key satellite contributions have important food and agriculture implications. The GEOGLAM (Group on Earth Observations Global Agricultural Monitoring Initiative) of the G20 coordinates mass use of EO data from coarse resolution instruments such as MODIS and medium resolution imagery and SAR data from Sentinel in order to inform agricultural systems and monitor food price volatility across regions.[xxiii] The challenge remains to move from research purposes towards systematically robust operational capacity. This step has the potential transformative effect sought for the SDGs. Large scale international coordination is already carried out through sophisticated partnerships like the Famine Early Warning System, which are difficult to replicate meaningfully with large capital injection.[xxiv] However, localized approaches show great promise, as well.

Agriculture and Ecosystem Policy Recommendation #1: Crop Residue and Tillage

- Use Landsat SWIR band to map crop residues leftover after harvest seasons with high accuracy above 90% on average[xxv]
- Create policies to incentivize and financially reward (tax, insurance, cash, etc.) small farm holders who implement conservation tillage
- Land degradation is increasing rapidly in Africa and creating many ecosystem and water issues. This policy increases sustainable agriculture (SDG 2.4) and will help grow agricultural productivity in successive years for small holder farmers (SDG 2.3)
- Financial incentives will increase agricultural incomes in return for positive externality benefits for public stakeholders (i.e. local and national government)

Agriculture and Ecosystem Policy Recommendation #2: Forest Preservation

- Use commercial high-resolution imagery data to validate ecosystem services (paying landholders not to cut down trees)
- Randomized trial found program directly successful in reducing tree-cutting in Ugandan private forests, while program benefits from carbon dioxide sinking were valued at almost three times the program cost [xxvi]
- Expansion to key climatically temperate African countries below the desert belt will help protect forests (SDG 15.2) and biodiversity and reduce desertification spread (SDG 15.3)

- Direct action will have a 5-10% reduction effect on deforestation in implementation areas based on efficacy of previous trials

2.6.3 Electrification and Power

2.6.3.a Increasing Electric Power Reliability By Monitoring and Displaying Power Outages in Near-Real Time

- **Relevant SDG Targets**
  (SDG 7.1) (SDG 7.b)

Electric power outages and instabilities are frequent and common occurrences in Sub-Saharan Africa. This leads to increased costs, lost economic opportunities, and reliance on polluting diesel fuels. Researchers at Carnegie Mellon established that excessive generator use leads to increased air emissions in all country scenarios.[xxvii]

<u>Electric Power Policy Recommendation #1</u>: Bring Power Outages to Light

- Utilize VIIRS night light data to create an automated daily index of electric power outages among all major African cities
- Data cleaning and processing methods have been adequately vetted and qualified.[xxviii] The methodology is appropriate for the creation of a near-real time (daily) web interface for open monitoring
- The creation would spur a new, novel knowledge base for outage events previously inaccessible by existing data methods (SDG 7.1 – reliable energy). It also incentivizes improvements in the system and a platform technology for local innovation communities like startups (SDG 8.5)
- It is possible for significant action to occur in at least 1-2 countries who act as leading adopters to systemically address power reliability in response to the data publishing, which is a significant contribution to SDG #7

2.6.4 Internet Connectivity

2.6.4.a Propelling Educational Equity and Gender Parity through LEO Satellite Internet Access Expansion in Remote Areas

- **Relevant SDG Targets**
  (SDG 9.c) (SDGs 4.1 through 4.7) (SDG 5.5) (SDG 5.b) Connecting the Unconnected

Satellite internet has long been available, and though not necessarily a remote sensing technology, it is considered important for inclusion in the context of this study. It was also identified in the previous net impact score analysis as one of the most effective direct satellite technologies contributing to the SDGs. Historical challenges in uptake have included high costs as compared to mobile or terrestrial networks and low throughput of GEO (geostationary orbit) satellites which orbit around 36,000km from Earth. New advances in technology have seen LEO (low-earth orbit) constellations be able to provide high-throughput internet readily. Companies such as SpaceX (Starlink) and OneWeb are active in this space. Costs can still be high per unit in some cases but are expected to fall gradually. Mozambique became the first African nation to partner with Starlink for expansion on the continent. A substantial amount of the unnetworked population in Africa would be best-served by satellite technology, and a large amount of critical infrastructure like schools and community centers, and health clinics would benefit from the same. Rwanda has previously partnered with OneWeb to launch a satellite specifically for connecting rural schools.[xxix] However, new satellite launch is likely not necessary for most cases. Rather attention should be focused towards licensing for existing companies, communications regulations and band allocation, and incentivizing or negotiating direct partnerships with critical private institutions.

Internet Connectivity Policy Recommendation #1: Introduce Competition for LEO internet providers and Anchoring Partnerships

- Utilize market incentives of competition to lower costs of user terminals in order to increase affordability and uptake
- Pair this with special, government-led prioritization of critical infrastructure like rural schools, health clinics, community centers, and banks to secure competitive service rates and critical mass for large-scale deployment in a country
- Evidence shows that reliance on end-user uptake from the general population skews towards the highest income resident whom are less likely to require satellite internet services, and therefore, demand is not enough to sustain new entrant providers[xxx]
- Sub-Saharan Africa has the lowest number of internet users at 22%, and LEO constellations have the opportunity to double this number by 2030 (SDG 9.c), contributing critically to the full range of SDG 4 (Quality Education) targets, as well as gender parity through connection of women to the internet in particular (SDG 5.b)

2.6.5 Social Protection

2.6.5.a Pairing Poverty Mapping Methods with Government Validation and Direct Assistance to the Poor and Vulnerable Populations

- **Relevant SDG Targets**
  (SDG 1.1) (SDG 1.2) (SDG 1.3) (SDG 1.a) (SDG 1.b) (SDG 11.1)

Much has been written about poverty mapping potentials with satellite remote sensing data. Landsat data and night light data have been used in tandem with existing household surveys for result validation.[xxxi] Other methodologies call for the use of cell phone usage data in tandem with satellite imagery to generate the highest accuracy.[xxxii] Slum location mapping has also been used by detecting unique features in urban landscapes associated with lower quality housing, for example, thatched roofs or lean-tos.[xxxiii] Another study has attempted to characterize upward mobility for poor communities using imagery data.[xxxiv]

<u>Social Protection Policy Recommendation #1</u>: Direct Assistance to Poor Households & Neighborhoods Using Satellite-Aided Mapping

- Utilize success of Togo's Novissi program as a baseline and gold standard for effectiveness of social support systems that are agile and adaptable in using imagery to validate and supplement governmental data [xxxv]
- Develop context-appropriate policies (Togo used direct cash transfer during the special circumstances of the COVID-19 global pandemic. This may not be appropriate for all situations)
- Careful attention must be paid to not reinforce biases due to poorly vetted algorithms or differential effects of missing data points or people in the system
- Social protection floors (SDG 1.3) are strongly recommended to be implemented, which have threshold triggers, as the majority of informal workers live on daily income (or for farmers, live on harvest season schedules) which could fluctuate at any time making prediction difficult

2.6.6 City Vital Signs

2.6.6.a Increasing Urban Greenspace by Prioritizing Re-fragmentation and Ecosystem Benefits

- **Relevant SDG Targets**
  (SDG 11.7) (SDG 15.5) (SDG 15.9)

A large number of satellite remote sensing methods can feasibly be applied to improving the health, functionality, and safety of cities. One interesting use case that has not seen extensive revision in the literature is the connectivity of greenspaces within cities and urban planning. Kowe et. al. reviewed advancements and applications of vegetation fragmentation and found that very few comparative studies exist weighing cities against one another and that Africa in particular has a paucity of analysis done.[xxxvi] One reason for this may be cloud cover issues over tropical regions but more likely there has not been active participation or inclusion of researchers from these regions. One study in Turkey compared the fragmented vegetation corridors of the coastal cities of Rize and Trabzon and suggested green corridor networks for both, an example of ecological planning in cities. This is feasible in many African cities and has a host of synergistic benefits including increasing natural habitat spaces for native flora and fauna, lowering the land surface temperature, and increasing quality of life and development when paired with economic or social development plans. Survey results of a study investigating public administrative use of satellite-based services indicate that local authorities require more assistance than regional or national administrations to implement satellite solutions.[xxxvii]

<u>Urban Policy Recommendation #1</u>: Connecting and Expanding Greenspaces by Natural Vegetation Patterns

- Utilize data from high resolution commercial imagers (ex. SANSA space agency in South Africa has an existing research partnership with SPOT) to analyze and plan green corridor ecological extensions in major cities
- Pair national or regional agencies possessing significant remote sensing capacity with local municipal government officials and policymakers who will be the end users
- Advocate also for public involvement in planning process and awareness around the benefits of satellite technologies in providing a birds-eye view of their city
- Africa is an increasingly urbanizing continent which the UN projects will reach 70% urban dwellers with an exceedingly young population that needs access to public spaces (SDG 11.7). Projects can also build public pride and engagement in the betterment of urban spaces for all.

2.7 Conclusions

Satellite remote sensing technology uses are incredibly diverse and malleable to the needs of the end users. New uses are appearing increasingly and limited only to creativity of the users. In fact, at the present juncture, more satellite data exists than processing power to possibly utilize it all effectively. Current use levels are well under optimal capacities, however, across all uses areas. Barriers to utilization of remote sensing products are slowly decreasing over time in coincidence with higher public awareness and accessibility to the remote sensing related services. Still more needs to be done to vastly expand the current uses. The Sustainable Development Goals can be greatly aided in their achievement by implementing large, targeted expansions of current utilizations, especially on the African continent. This study section has presented and justified a robust index classification system for quantifying and communicating the benefits of remote sensing on SDGs to a broad audience. In additional, specific policy avenues according to strategic, thematic impact areas have been advocated based on highly relevant use cases and methodologies that require expansion. It is strongly suggested that these methods be implemented in a timely manner, at-scale in order to aid achievement of the SDGs for Africa and the world at large. In the next section, we will explore the domestic satellite capabilities of African nations and trends in their growth and coordination efforts, as well as policy avenues that allow for maximum utility of new satellite data for specific uses.

Chapter 3

Africa's Domestic Satellite Industry: Status, Opportunities, and Future Growth Potentials

3.1 Introduction

Satellite launch and operation activities have long been dominated by major international players such as the United States and Russia, as well as China, India, and the European Union. Though data-sharing policies and provisions exist for giving worldwide access to medium-resolution EO data from missions such as Sentinel and Landsat or allowing ubiquitous use of GPS and GNSS positioning services, many limitations still remain in accessing the full breadth of satellite data possible. Access to commercial high-resolution imagery – such as from WorldView or SPOT satellites – that is used in applications like Google mapping services and precision agriculture is restricted and cost-prohibitive in many cases. Many mission critical infrastructures like banking and aviation depend on continued use of satellite services. Development of space capability was identified by the African Union in their 50-year sustainable development plan, the Agenda 2063, as a flagship project. About their Africa Outer Space Strategy, the African Union states the following:

> *"Outer space is of critical importance to the development of Africa in all fields: agriculture, disaster management, remote sensing, climate forecast, banking and finance, as well as defence and security. Africa's access to space technology products is no longer a matter of luxury and there is a need to speed up access to these technologies and products."*[xxxviii]

The African Union also outlines in their Space Strategy report that the African continent makes up 20% of the Earth's total land surface area but Africa's $100 million USD collective investment in space in 2013 represented less than 0.2% of the space budget globally.[xxxix] Many space-derived services in communications, positioning, and earth observation have provided large benefits to the African continent overall but, to a large degree, African nations themselves have not been significant participants in these technical activities.[xl] New opportunities for disease prevention, natural disaster response, climate change adaptation, food security, and rural and urban connectivity have still yet to be fully developed and utilized.

3.2 Research Question

The main research question investigated in this section is how is domestic African satellite activity and technical capacity development contributing to sustainable development aims on the continent?

3.3 Methodology

The study was conducted by carrying out a systematic review of available public databases, peer-review publications, industry reports, and national space agency documentation. This began with broad data collection using a systematic style of review from the available sources. The aim was to determine trends in how the satellite industry is growing domestically in African nations and what technical capacity implications this has. It can be observed that differential effects and levels of activation exist in different nations.

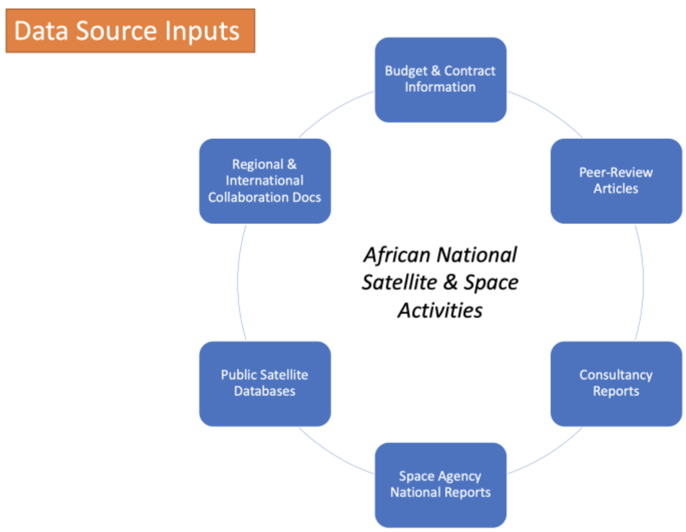


Figure 3-1: Data Collection Scope

A classification methodology around satellite activity was developed to help policymakers and onlookers alike understand the dynamics of the various African nations' level of growth. The classification also helps orient new audiences to the dynamics of the African satellite space. Many even in the space industry are unfamiliar with the high level of activity represented in the sector. Lack of visibility is arguably a concern of itself and limits synergistic opportunities and symbiotic new potential partnerships with both local and foreign parties. The study scope was also able to identify gaps in African space policy approaches that are derived from inadequate attention given to data policies governing satellite missions after launch; that is that data is seldom available to the public or shared beyond the directly responsible operating entity. Amplification effects from open data policy implementation is a large missed opportunity for the African space and sustainable development communities as a whole. It is recommended that the role of the emerging African Space Agency become leading in this regard and also in coordinating joint mission efforts and shared use of manufacturing, testing, and integration facilities in the future.

3.4 Background

A number of African nations have been active in space and remote sensing for several decades, hosting their own remote sensing or space agencies and even launching satellites in many cases. Nigeria, Morocco, South Africa, Egypt, and Algeria each have launched at least three national satellites and have historically been among the most active African nations in space activities. Many new entrant satellite nations in African have also recently launched, due in large part to the lowered manufacture and launch barrier to entry opportunities that have accompanied the widespread adoption of modular nanosatellites, commonly known as CubeSats. Some nations have built entirely independent design and manufacture capacity while others opt for a collaborative approach with other nations and contractors, while some still have pursued a mixture of both. This research offers a classification mechanism for conceptualizing these varying activation pathways and how this affects sustainable development aims. Regional partnerships, the establishment of the African Space Agency, and data-sharing policies (or a lack thereof) are also considered in the context of realizing full potentials from current and future satellite activity on the continent.

Among the challenges identified by the African Union Commission around building collective African capacity in space are disparities in space expertise across nations, lack of qualification of African user needs, duplication of efforts and lack of coordination between and within nations, political instability, over-reliance on financial and technical support from outside the continent, brain drain of core skills, and a lack of coordinated approach to international treaties regulating space.[xli] SWOT analysis also highlighted strengths and opportunities which include the current existence of nodes for space expertise, political support for space and socioeconomic benefits, existence of assembly, manufacture, integration, and testing facilities, a rural and geographically diverse population which can be well-served by space technologies, potential to share infrastructure across nations and increase cooperation, and ability to leverage existing skills in the African diaspora. This study analyzes advances in African space activity in recent years, building on previous work in the domain, and how specific nations conceptualize and build sustainable development capacity through their respective satellite programs.

Debate exists around the question of prioritizing space activities in African nations when many competing needs exist in parallel, for example, healthcare, infrastructure, education, and climate change. Critics highlight the large costs – multi-million to multi-billion-dollar budgets – required for substantial presence in space-related activities and highlight in juxtaposition the many parallel societal challenges faced by residents of the African continent including high inequality, the rural-urban divide, educational disparities, unemployment and underemployment, food insecurity, and worsening vulnerability to climate change as more immediate concerns. Considered in the context of political support, it is pertinent to consider this dynamic, as present popular support does not guarantee continued public support, particularly for diverse groups of stakeholders. Historical context from the US Civil Rights Movement is illuminating because the Apollo Program was contested by prominent leaders in the Southern Christian Leadership Conference (most well-known for its charismatic leader Martin Luther King Jr.) such as Ralph Abernathy who referred to the 1969 moon landing as an example of America's 'distorted sense of national priorities' while the poverty rate in American was three times higher for African-Americans in the same year.[xlii] Previous studies have found that many non-technical aspects influence motivation to pursue space policies, main among them national pride, regional status, and geo-political positioning.[xliii] Military-security framework has been explored as a historical dynamic to certain African nations' space activity during the Cold War period (e.g. South Africa, Egypt, and Libya) and similarly as a potential dynamic during the current 21st century era where military and security concerns can also contribute to national decisions to pursue space policy, particularly those with substantial military and security apparatuses.[xliv]

Perhaps the most apt sources of comparison are African nations themselves, particularly countries which have been active in space for a number of years. Data utilization from the current EO satellites is quite low, and data is not even publicly available in many cases. Cooperation and data sharing is also low between national agencies. SANSA has made innovative data agreements such as 2006 agreement with Airbus to provide free data access from SPOT 5, 6, & 7 missions to government and academic institutions, which is a significant lowering of barriers to entry and cost burden for use of high-resolution commercial satellite imagery that often faces remote sensing end-users.[xlv] The African Resource Management Constellation (ARMC) was a project proposed in 2002 and agreed upon in 2009 to launch a regional African satellite constellation to practice preventative disaster management. Of the four nations agreeing to participate – Nigeria, Algeria, Kenya, and South Africa – only Nigeria has successfully launched an EO satellite mission, NigeriaSat-2 in 2011, towards the constellation. Launch plans of AlSat-3 (Algeria) and EO-Sat1 (South Africa) have been pending, so it remains to be seen the ultimate success of the stalled project. Meanwhile, NigeriaSat-2 is nearing end of its useful life and is past its designed use date as of 2018. The RASCOM (Regional African Satellite Communication Organization) satellites aimed to provide broadband services, telecommunications, and internet access to the African continent, particularly rural areas, and successfully launched two GEO satellites. The satellites, though achieving some goals, failed to fully achieve ambitious targets due in part to organizational changes, turnover, low-throughput, and suboptimal uptake of services.

3.5 Results

3.5.1 Space Agencies in Africa

Historically, the first space agencies in most African nations and globally were conceived as remote sensing or geospatial data agencies. This is the case with Sudan, the first such agency established in Africa, in 1977 with the National Remote Sensing Center. This agency was retooled as the Remote Sensing Authority in 1996. Tunisia set up the National Remote Sensing Center of Tunisia in 1988. Also, in 1989, Morocco established the Royal Center for Remote Sensing and in the same year, Libya launched the Libya Center for Remote Sensing and Space Science in 1989. Similarly, the National Authority for Remote Sensing and Space Sciences (NARSS) was established in Egypt in 1991: This became the Egyptian Space Agency in 2018. These five nations had the first formalized remote sensing departments among regional peers in Africa. They were followed by space agencies in Nigeria, Algeria, Ethiopia, South Africa, Gabon, and Ghana.

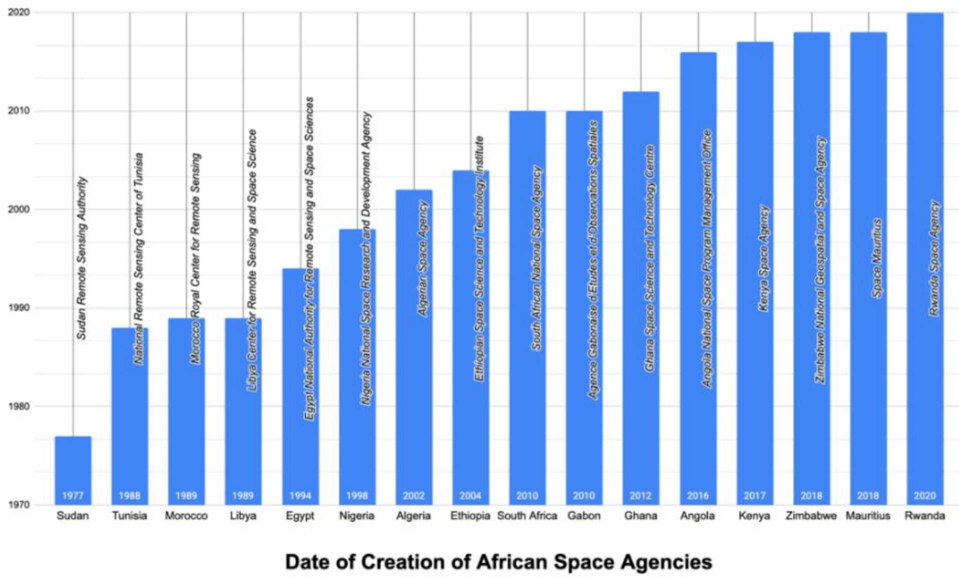


Figure 3-2: African Space Agencies

New space budgets in Africa are being allocated on a yearly basis with new nations formally establishing space-related government agencies increasingly. Currently, 20 African states have a space or remote sensing office.

3.5.2 Space Budgets in Africa

Budget allocation is a good proxy for complexity in many cases. The largest budgets by total spending are seen in South Africa, Angola, Egypt, and Nigeria. Funding has declined significantly in Angola due in large part to the devaluation of their local currency. New space agencies tend to start with modest budgets primarily aimed towards nano-satellite development, training and capacity development for a dozen to tens of satellite engineers, and development of ground station capabilities. Examples of such nations include Kenya and Mauritius, which both recently launched nanosatellite CubeSats as their first national satellite projects, though Kenya has been active in the space industry for an extended time. National space agency budget data gathered here was sourced from Space in Africa's database, as well as from annual reports and satellite bidding cost figures, where applicable.

Size of Space Budgets Are Associated with Length or Extent of Involvement with Space Activities

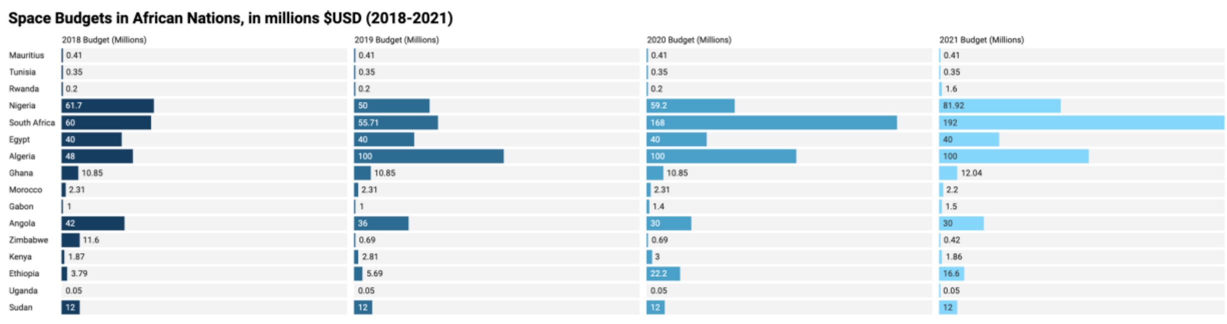


Figure 3-3: African Space Budgets

Budget information was not readily available for the following countries: Sudan, Mauritius, Rwanda, and Tunisia. Budget figures here were determined from annual reports and satellite cost documents, so it is likely that they are underestimated in terms of total budget allocation. Sudan's SRSS-1 satellite, which was contracted to a Chinese firm Shenzhen Aerospace, cost $12 million USD in 2019. The Mauritius Research Council's 2018-2019 Annual Report recorded a Rs 7.3 million payment (approximately $205,000 USD in 2019) to Clyde Space Ltd 'for satellite'. The consultancy Space in Africa's proprietary report states a $412,000 USD cost for Mauritius' MIRSat-1 satellite, indicating that payment was likely made over a two-year period. RwaSat-1 CubeSat of Rwanda launched in 2019 is estimated at $200,000 USD by Space in Africa. Their national space budget allocation was $1.6 million USD in 2021. Tunisia's Challenge-ONE was built in 2021 at a cost of $350,000 USD though no national space agency budgets were declared. Tunisia's satellite development is unique in that it was completed commercially by Tunisian company TELNET, which carried out design and operation of the satellite. Budget information for a number of space agencies with military affiliations in these countries remain classified.

Some nations have accelerated their budget allocations in the last few years. South Africa's space budget allocation has grown from $60 million USD and $55.7 million USD in 2018 and 2019, respectively, to $168 million USD and $192 million USD in 2020 and 2021. South Africa has the most well-funded space agency among African nations as of 2021. Algeria has also increased budget allocations in recent years going from $48 million USD in 2018 to $100 million USD annually for 2019, 2020, and 2021. Nigeria, a well-established space nation having launched its first satellite Nigeriasat-1 in 2003, had a space-related budget of $81.9 million USD in 2021 growing from $61.7 million USD, $55.71 million USD, $59.2 million USD in the years of 2018, 2019, and 2020, respectively.

3.5.3 Overview of Missions

African satellite launches have grown noticeably in the past decade. Historically, space activity on the continent was dominated by South Africa, Egypt, Nigeria, Algeria, and Morocco in terms of satellite launches with additional early activity in remote sensing from nations like Kenya, Ghana, and Sudan. The 2010s have seen a proliferation of African nations entering space for the first time. Many more established space nations in Africa have also began launching follow-on missions to their legacy satellites which were originally deployed in the 1990s and 2000s. Egypt launched four satellites – TIBA-1, EgyptSat-A, NARSSCube-2, and NARSSCube-1 – in 2019 alone. Algeria, Morocco, and South Africa have also launched similar clusters of satellite missions. New entries to space have been logged by Angola, Sudan, Ethiopia, Kenya, Rwanda, Mauritius, Tunisia, and Ghana.

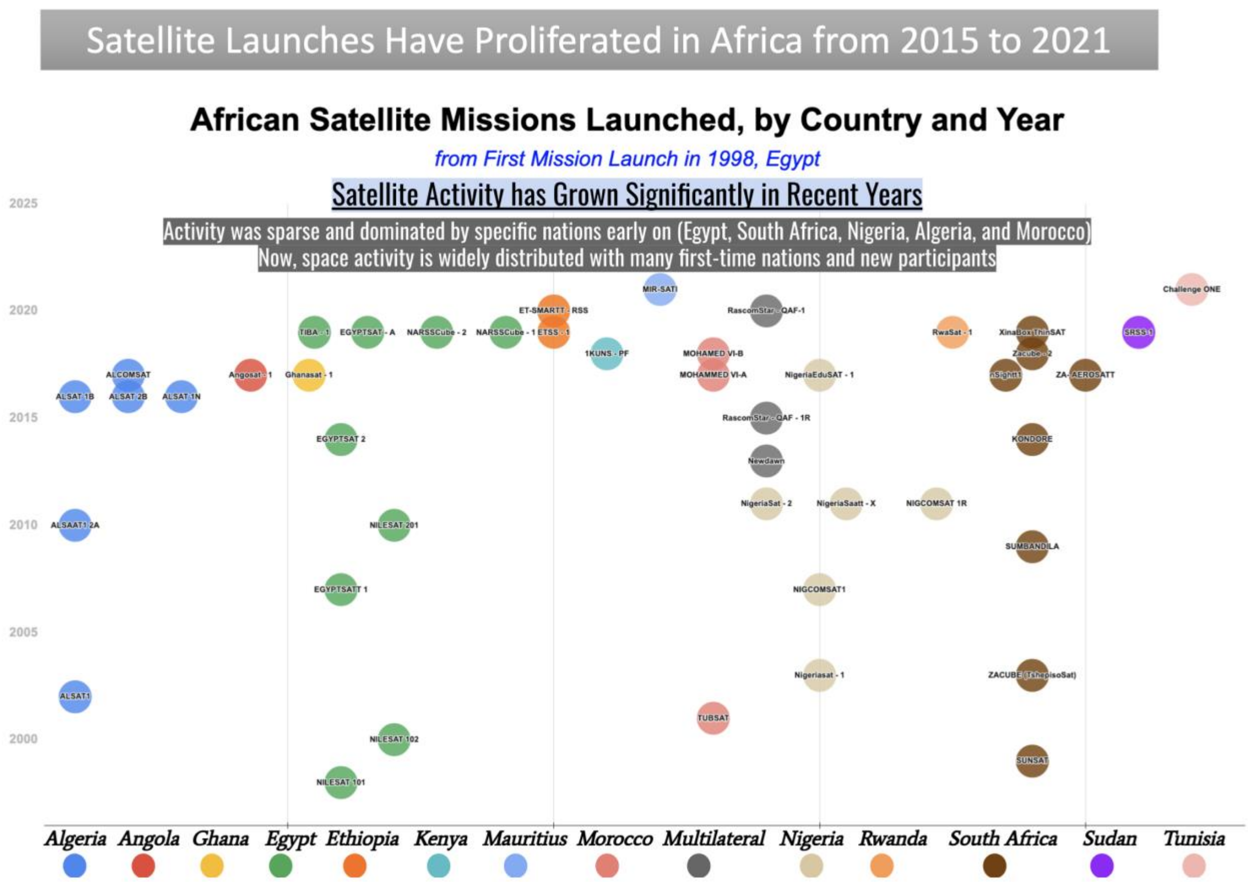


Figure 3-4: African Satellite Missions to Date

The overall space activities of African nations are small in comparison to the leading space countries, the United States, Russia, China, and India. However, when looked at next to the "Rest of World" (RoW) nations --- all nations excluding the (United States, Russia, China, and India) --- they are a large percentage of total activity. In fact, in 2019, African satellite launches made up over fifty percentage of total RoW satellite launches marking the first year for this occurrence. The countries of Africa are likely emerging as a regional block and making use of satellite earth observation, broadband, communications, and scientific missions. This is further evidenced by the establishment of the African Space Agency by the African Union in 2018.

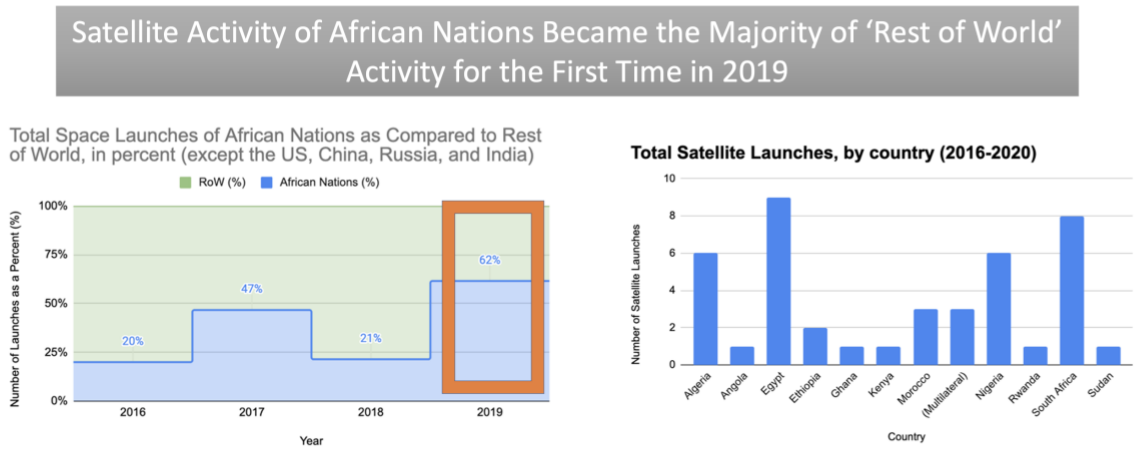


Figure 3-5: African Satellites Launches vs. 'Rest of World' Activity

According to data from the Union of Concerned Scientists (UCS) Database, the majority (54.3%) of satellites launched by African nations operate in LEO, or low-Earth orbit, while the remaining portion (45.7%) operate in GEO, or geostationary orbit. LEO is associated with many earth observing missions and scientific payloads which have a need to cover wider swaths of land on a periodic basis. GEO is linked to communications satellites and broadband services which have a need to cover a fixed area consistently. The average lifespan of satellites in orbit is 5.5 years with a 5-year median lifespan.

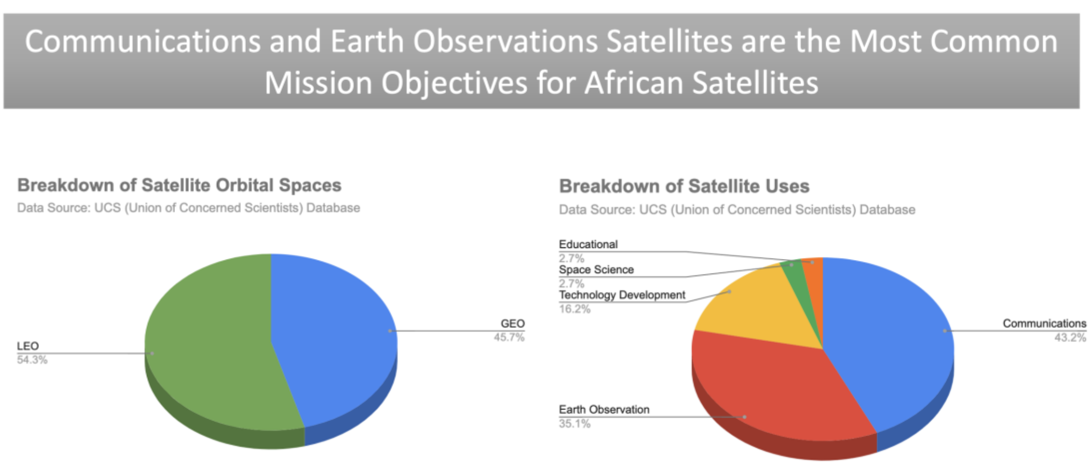


Figure 3-6: African Satellite Mission Objectives

Average Lifespan of Featured Earth Observation Satellites is 5.5 years, and Median Lifespan is 5 years.

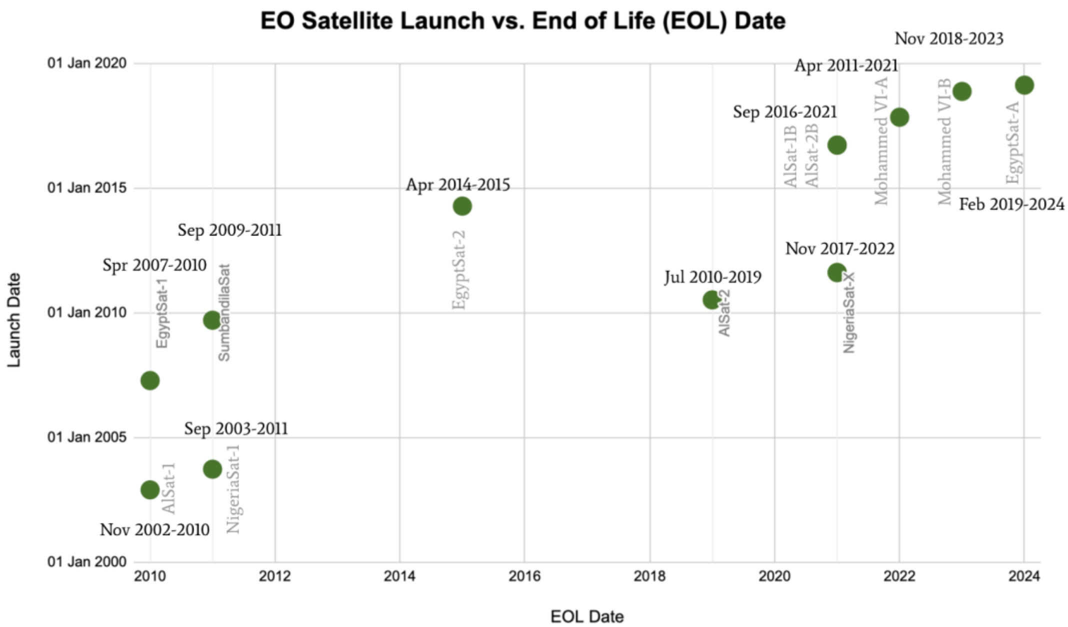


Figure 3-7: African Earth Observing Satellite Average/Median Lifespans

Uses of satellites vary between missions according to design intention and funding partner. A majority of missions have primary use in earth observation, followed by communications. Many also have military payloads or scientific payloads. Morocco's Mohammed VI-A & VI-B are both military missions with significant high-resolution imaging capacity and were launched as follow-ons to one another. The majority of satellite missions from African nations had primary missions in earth observation or weather monitoring, followed by science and technology missions, communications missions, and military or reconnaissance missions. Satellite missions have been used for preventative environmental monitoring (Kenya), assessment of climatic conditions in small island states (Mauritius), agricultural crop yields (Nigeria), and a variety of other uses.

3.5.4 National Profiles

Summaries of African national space profiles detail important origins of space activities and current projects being undertaken by each nation.

3.5.4.1. Algeria

The Algerian Space Agency was established in 2002. They have launched six satellites, including four satellites since 2016. Two missions have planned follow-ons in AlComSat-2, a communications satellite supplementing AlComSat-1, and AlSat-3, which includes high resolution earth observation capabilities. Algeria has one of the largest budget allocations of all active African space nations, behind only South Africa. In 2021, the budget allocation of the Algerian Space Agency was $100 million USD growing from $48 million USD in 2018. Growth plans are slated along the National Space Program Plan to 2040, which replaces the previous space program plan of 2006-2020. AlComSat-1, the nation's first communications satellite, was launched in 2017 and manufactured by the China Academy of Space Technology. Over the expected 15-year lifespan using 33 transponders, the satellite will provide digital radio and TV broadcast services, as well as 20 Mb/s internet speeds on Ka-band (high speed internet to Algeria) and 2 Mb/s mid-speed internet on Ku-band to users in North Africa.

3.5.4.2. Morocco

Morocco's national space agency – Centre Royal de Teledetelom Spatiale (CRTS) – was established in 1989 under the Ministry of Defense, so some of the projects are classified. Morocco launched Mohammed VI-A & Mohamed VI-B in 2017 and 2018, two high-resolution imager follow-on missions which serve military purposes. Morocco is a member of the Arab Space Cooperation Group. The country is also engaged in the Global Monitoring for Environment and Security (GMES) and Africa program, including the installation of two eStations in the country for earth observation data processing and reception. The two stations are located at Chouaib Doukkali University (UCD) and the African Regional Centre form Space Science and Technology in French Language (CRASTE-LF).

3.5.4.3. Egypt

Egypt's National Authority for Remote Sensing and Space Sciences (NARSS) was established as a governmental organization under the State Ministry of Scientific Research in 1994. They oversaw the launch and operation of 9 satellites including the first NILE-SAT1 in 1998, which was the inaugural satellite launched by an African nation. In 2018, the Egyptian Space Agency (EgSA) was legally established to in part to 'create self-capabilities to build and launch satellites from Egyptian territory' (citation). The agency operates two satellite control centers, one in the capital Cairo and another in Aswan to the south of the country. EgSA's 10-year plan includes many plans for satellite mission development and local satellite assembly and testing. The nation had a scheduled launch in December 2021 postponed of a new Egyptian satellite series named 'Next' with German and Chinese partners. The first of the series is a 65kg satellite purposed for remote sensing and scientific research. Other planned launches include March 2022 for a group of nanosatellites and September 2022 for the launch of Egypt-Sat2. In addition, the MisrSat2, a new experimental satellite, is slated to be manufactured in Egypt. Strategically, Egypt has also established a project with NASA for 35 educational CubeSats to train more satellite engineers in the country, as well as with the United Nations Committee for the Peaceful Uses of Outer Space to launch an earth observation satellite. The EgSA plans to deploy an Egyptian astronaut to the International Space Station, and Egypt was selected in 2020 as host of thew proposed African Space Agency at the 32nd Session of the African Union Assembly.

3.5.4.4. Nigeria

Nigeria's National Space Research & Development Agency (NASRDA) came into being in 1991. Nigeria has launched six satellites to date, with the most recent satellite Nigeria EduSat-1 in 2017 being the first built by a university (Federal University of Technology Akure) and was done in conjunction with the BIRDS-1 program of the Kyushu Institute in Japan. Three Nigerian satellites are no longer orbiting: NigeriaSat-1, NigComSat-1 (Africa's first communications satellite), and EduSat-1. NASRDA also reports that NigeriaSat-2, and earth observing satellite mission, has become obsolete. This effectively leaves NigComSat-1R, a communications satellite with a design life until 2025, and NigeriaSat-X, an Earth observation satellite also past its design life. NASRDA has plans to replace old satellites in their fleet with Nigeria Sat-3 (optical earth observation) and NigeriaSAR-1 (synthetic aperture radar). These represent the first major satellite projects the agency has developed in a number of years. The country is developing new national space strategy policies and plans to locally manufacture a CubeSat project. Recessions and devaluation of the Naira in relation to foreign currency had impacted the country's space budget.

3.5.4.5. South Africa

South Africa's space activities are organized under SANSA, the South African National Space Agency. SANSA has the largest operating budget of all space-active nations in Africa. In 2021, their total budget allocation sat at $192 million USD. South Africa has launched a total of (8) satellites to date, including 5 launched since 2010, and hosts a substantial upstream and downstream companies in the local commercial space sector. SANSA has signed several memorandums of understanding (MOUs) with the purpose of advancing work and partnerships in the following fields: earth observation, science policy, climate research, malaria, and nanosatellite.

3.5.4.6. Tunisia

Tunisia launched the first national satellite ChallengeOne in 2021 together with Tunisian telecommunications company TELNET which managed design, build, and operations. Future plans include launching a 24-30 satellite constellation to connect the Internet of Things (IoT) in the next 2-5 years. Tunisia stands out among 'Early' space nations in Africa by having an entirely national process for their first satellite launch -- the strategy was to recruit the best and brightest engineers from Tunisian universities before they had a chance to emigrate. Support was received from teams in Toulouse, France and Moscow, Russia, along with Tunisian diasoprans such as an engineer who worked on NASA's Perseverance Mars rover.

3.5.4.7. Kenya

Kenya has pursued an international cooperation model of satellite development with Italy. The Kenyan Space Agency works as a subset of the Kenyan Defence Ministry with a budget allocation of 0.017% of the total USD 1.10 billion spending of the Defence Ministry in 2018. By 2020, the space budget had increased from USD 1.87 million in 2018 to USD 3 million, where it has stabilized. In 2018, the University of Nairobi, in collaboration with the University of Rome (Sapienza Università di Roma) designed and built Kenya's first satellite, the 1KUNS-PF, which was the first CubeSat launched by the KiboCube Program of JAXA and UNOOSA to monitor agriculture and coastal regions. Kenya also penned a deal with Italy in 2020 allowing use of the Luigi Broglio Malindi Space Center in southeast Kenya at USD 229,000 annually.[2] Kenya also has plans to launch two more nano-satellites using high- altitude balloons in partnership with Sapienza Università di Roma as part of Kenyan Space Agency's continued capacity- building plan.

3.5.4.8. Sudan

Sudan established the National Remote Sensing Center in 1977 and reorganized it into the Remote Sensing Authority in 1996. Space activities have been present at university institutions such as Future University (program in space science and engineering) and University of Khartoum (1U CubeSat design of KN-SAT1 and KN-SAT2 and operational ground station for geospatial data). The nation launched their first satellite SRSS-1 in 2019, designed and built by the Chinese company Shenzhen Aerospace Dongfanghong HIT Satellite Ltd with the intention of also building local operational capacity at a ground station in Khartoum North. SRSS-1 is a remote sensing satellite to create topographic maps and monitor resources for agriculture and natural resources (as well as military and surveillance capabilities). Plans to launch a Sudanese communications satellite SUDASAT-1 have been announced, but it is unclear if the project will move forward.

3.5.4.9. Ghana

Ghana has allocated a steady budget of USD 10.85 million annually from 2018 - 2020 to the Ghana Space Science and Technology Institute, which is an arm of the Ghana Atomic Energy Commission.[2] Much capacity is also located at All Nations University, a private university in Koforidua, Ghana, at the Space Systems Technology Laboratory. Ghana's first satellite Ghana-SAT1, a 1U science education and optical remote sensing CubeSat, was launched in 2017. The satellite took the efforts of three students at All Nations University, two years, and approximately USD 500,000 from the institution to develop and was completed in partnership with Japan as a part of the Kyushu Institute of Technology's Joint Global MultiNation 'Birds' Satellite program. Development has been bolstered by providing incentives to scientists and experts in the diaspora to return to critical posts at universities and government posts.[5] The Space Systems Technology Lab has announced intentions to complete work on GhanSat-2.

3.5.4.10. Mauritius

Space activities for Mauritius are managed under the Mauritius Research and Innovation Council (MRIC). The nation launched MIR-SAT1, their first satellite, in June 2021 through the KiboCube program of JAXA and UNOOSA to deploy CubeSats from the Japanese Experiment Module 'Kibo' arm of the International Space Station, particularly for education, research, and capacity-building for new spacefaring nations. The payload carries a commercial camera and experimental module for 'island to island' communication. MRIC annual reporting indicates payment to Clyde Space Ltd in fiscal year 2018/19 for USD 7.32 million for the design and delivery of the satellite. Also, according to the 2019/20 procurement plan, plans are underway for satellite ground station antennas and installation. Mitigation efforts are a priority for Mauritius as a small island nation state. Satellite operations are carried out at a ground station at the MRIC premises in Ebene, Mauritius, and plans to set up a Mauritian Space Unit and launch a 3U CubeSat mini satellite constellation to gather data from the Exclusive Economic Zone are underway.

3.5.4.11. Ethiopia

Ethiopia's first satellite ETRSS-1 was launched from a Chinese Long March 4B rocket in December 2019. ETRSS-1 is a satellite of mass 65 kg with a multi-spectral imager onboard, delivered by Chinese partners CAST (China Academy of Space Technology) and subsidiary DFH Satellite Company Ltd. The ground station capabilities are centered at the Entoto Observatory and research center in Addis Ababa. Satellite data products have been used for applications in many sectors such as infrastructure monitoring, water resource maintenance, and agricultural yield. In addition, strides in technical development have been made with twenty-one Ethiopian engineers and scientists having been trained in satellite engineering and science. The Ethiopian Space Science & Technology Institute received a budget allocation of USD 3.79 million in 2018, USD 5.69 million in 2019, and USD 5.69 million again in 2020, with other related geospatial operations in government also receiving increased allocations. Ethiopia is ongoing in the building of satellite manufacturing, assembly, integration, and testing facilities in the capital.[2]

3.5.4.12. Rwanda

The Rwandan Space Agency was formed in 2020. According to the Space in Africa consultancy, no official budget has yet been released for the space agency's operations.[2] RWASAT-1, a 3U CubeSat, was launched in November 2019, built by Rwandan engineers in collaboration with JAXA, the University of Tokyo, and the Japan International Cooperation Agency (JICA). Five Rwandan engineers worked directly with the University of Tokyo team on design and build of the satellite and another fifteen engineers were also provided training in satellite technology. The satellite payload is equipped with a receiver for ground-based sensors and two onboard optical cameras for data collection on 'water resources, natural disasters, agriculture, and meteorology'.[5] Earlier in February of 2019, Rwanda effectively launched its first satellite "Icyerekezo", a broadband satellite designed to bring internet connectivity to rural schools in the country, built in partnership with UK-based company OneWeb. Rwanda has expressed intention to further leverage improvements in Earth observation technology and to increase the affordability of data with new space missions.

3.5.4.13. Angola

Angola has a notable national space budget with a USD 42 million allocation from 2018, USD 36 million in 2019 and USD 30 million in 2020.[2] Recession and budget downsizing effects are apparent - still the Angolan Space Program Management Office is well funded in mean comparison to similar African peer nations, such as Ethiopia and Ghana. Angola has several ongoing international partnerships with the University Space Engineering Consortium (UNISEC), Airbus, Thales Alenia Space, and the European Space Agency (ESA). AngoSAT1, a USD 300 million communications satellite and Angola's first, was launched in December 2017. The satellite lost communications one day after launch, only restored briefly, and was ultimately declared officially defunct 4 months after launch and orbit. Unfortunately, this means that the improvements to internet access and radio and tv broadcast expected with the satellite launch are yet to be realized, though Russian contractor RKK Energia has committed to rebuild the satellite at no-cost per insurance policy agreements. Angolan efforts in capacity-building have trained 71 members of staff internationally, with 4 of those being doctorate holders and nineteen being master's graduates.[13] In addition, updates to ground facilities are underway to support new satellite data management capabilities. Two subsequent missions, AngoSAT2 and AngoSAT3, are slated for launch by 2025.

3.6 Classifications of Space Nations in Africa

For classification considerations, a focus specifically on satellites was preferable to measuring space activities and technical capacity development because of the highly specialized nature and inherent requirement for unique engineering skills ranging from design of subsystems to testing and fabrication of satellite to launch and ground operation support. In other words, satellite activity in particular is an appropriate representation of overall complexity and capacity of a national space agency. Satellite design and testing procedures are often lengthy operational processes that involve dozens to hundreds of engineers, access to significant capital investments, and have lifespans of projects ranging from a few years to a few decades in typical cases.

Classifications of "Established, Early, and Nascent" space nations are defined, as follows:

- **Established**: Successful design, build, and launch of more than 2 satellites. For African regional nations, these countries include Nigeria, Egypt, Morocco, South Africa, and Algeria.

- **Early**: Successful design, build, and launch of 1-2 satellites. The 'Early' satellite nations in Africa include (Kenya, Sudan, Ethiopia, Mauritius, Ghana, Rwanda, Tunisia, and Angola).

- **Nascent**: Plans to launch a satellite have been established with design stages completed and build plans set in some cases. Some nations have established national space agencies. Identified 'nascent' satellite nations in Africa include (Zimbabwe, Burkina Faso, Senegal, Uganda, Gabon, Cameroon, Ivory Coast, Namibia, Djibouti, Libya, Botswana, and Democratic Republic of the Congo).

In most cases, the age of space agencies in 'established' satellite nations predates the formation of similar agencies in 'early' satellite nations, but this is not always the case. Space activities in Kenya, for example, have been going on for several years. Similarly, the National Remote Sensing Office in Sudan was established in 1977, among the first of all African nations. Their first satellite, SRSS-1 was launched in 2019.

Five Nations Have Historically Been the Most Active in Space and Satellite Development in Africa

Classification of Space Nations in Africa		
1. Established Space Nations	**2. Early Space Nations**	**3. Nascent Space Nations**
(Have launched more than 2 satellites)	(Have launched 1-2 satellites)	(Have not yet launched a satellite)* *May have satellite design plans or established space agencies already
Algeria	Angola	Botswana
Egypt	Ethiopia	Burkina Faso
Nigeria	Ghana	Cameroon
Morocco	Kenya	Democratic Republic of the Congo
South Africa	Mauritius	Djibouti
	Rwanda	Gabon
	Sudan	Ivory Coast
	Tunisia	Libya
		Namibia
		Senegal
		Uganda
		Zimbabwe

Table 3.1: Classification of Space Nations in Africa

Among "Early" African space nations, Tunisia has the most substantial private commercial satellite capability locally. The Challenge-One satellite was designed, built, and launched by TELNET in 2021, making it a commercial project from inception to completion. This is unique among "Early" space nations and also different to the development of all 'Established" space nations in Africa. The majority of early satellite projects are government-backed and funded through formal national agencies. Many also contract out the design and build duties to foreign partners, or pursue a collaboration model involving both foreign and local workers. Others are the initiatives of universities who have related departments and are interested in completing the design, and sometimes build, processes of nanosatellites. This was the case in Ghana featuring the All Nations University. The design stages and initiative for building process was spearheaded by university professors and students who eventually were able to secure funding from government sources and the BIRDS program of Kyushu University, culminating in the launch of GhanaSat-1, Ghana's first satellite in orbit. Many "Early" or "Nascent" stage space nations have local ground station operations in-country. Some, such as Ethiopia, build dedicated facilities to this end. Others utilize existing premises and retrofit necessary equipment to enable downlink capability with satellite missions post-launch.

Many nascent space nations in Africa are planning towards nanosatellite launches. Several nascent space nations have established responsible space agencies or allocated associated budgets. As identified in Erik Kulu's NanoSats Database, design on satellites commenced in Zimbabwe, Uganda, Djibouti, Burkina Faso, and Botswana through local universities, non-profit organizations, or the Kyushu Institute BIRDS (Joint Global Multi-Nation Birds Satellite) program in Japan. This program was pioneered in 2015 as a way to train students from developing countries on satellite and systems engineering methods over the course of a 2-year program. Ghana's GhanaSat-1 satellite launched in 2017 is s BIRDS program 1-U CubeSat. Engineers from Sudan, Kenya, Egypt, Ghana, Uganda, Morocco, Zimbabwe, and Nigeria have been trained through BIRDS at the Kyushu Institute.

3.7 Implications

3.7.1 Archetypes of Satellite Development Have an Impact on Use and Technical Capacity Development

As analyzed in Wood & Weigel, 2012, four satellite develop archetypes observed in developing nations were presented.[xlvi]

- **Turnkey Project:** This features a foreign firm contracted for the design and build of the satellite project.
- **Local University Project:** This features a local university responsible for the design and build of the satellite project. These are typically nanosatellites, or CubeSat projects.
- **Education Abroad with Local Development:** This features design and build of satellite by a local space organization and local university with training of personnel at a foreign university.
- **Collaborative Satellite Development:** This features design and build of satellite by local space organization and foreign firm in collaboration with training of personnel by a foreign firm.

In addition to these project archetypes, it is recommended that another project archetype also be added. This archetype represents the advancement of fully nation projects carried out by the private, public, or non-profit sectors in a country.

- **Fully National Project:** This features a national project designed and built by local satellite companies or space agencies. They can be governmentally pushed and funded or partially funded. These projects can still have strategic partnership involvement from other nations, but manufacturing is done in-house.

Fully national projects have particular significance to capacity building and local technical advancements. For example, in the case of Tunisia, the design and manufacture of Challenge-One by TELNET Holding reflects the robust commercial space economy that has developed in the country. Egypt, South Africa, and Algeria have also manufactured satellites in-country through the commercial sector, the national space agency, local university, or combination thereof. Many other nations are actively building similar capabilities, such as Ethiopia and Nigeria.

Early Satellite Nations and Their Pathways to First Launch

Country	Satellite Name	Development Type	Contractor or Program	Country of Partner	Satellite Size	Satellite Mission Use	Launch	Status
Kenya	1-KUNS-PF	Collaborative	Kibo-Cube Program	Japan	1U	Technology	2018	Operational
Mauritius	MIR-SAT1	Collaborative	Kibo-Cube Program	Japan	1U	Technology	2021	Operational
Ghana	Ghana-Sat1	Collaborative	BIRDS Program	Japan	1U	Technology, Education	2017	Not Operational
Rwanda	RWA-Sat1	Collaborative	University of Tokyo	Japan	3U	Technology, Education	2019	Operational
Angola	AngoSat-1	Turn-Key	RKK Energia	Russia	1647 kg	Communications	2017	Not-Operational
Sudan	SRSS-1	Turn-Key	DFH Satellite Company Ltd	China	50-100kg	Technology, Earth Observation	2019	Operational
Ethiopia	ETRSS-1	Turn-Key	China Academy of Space Technology	China	65 kg	Earth Observation	2019	Operational
Tunisia	Challenge ONE	Fully National	TELNET	Tunisia	3U	Technology	2021	Operational

Table 3.2: Pathways of Early Satellite Nations to Launch

It is interesting to compare the development archetypes of the two groups (Established & Early space nations) in regards to their first satellite projects. Characteristically, the two groups achieved orbit in different decades (1990s vs. 2010s). Tunisia's first satellite was fully national, which is unique. South Africa achieved this on their second satellite launch, for example. Characteristically, the outsourcing of satellite build and design for 'early' space nations is related to complex mission payloads. Generally, these are high resolution imagers intended for earth observation purposes or military payloads related to surveillance missions. All large satellites launched from Africa were outsourced to external contractors.

3.7.2 Nanosatellites Have Led to a Growth in Adoption

Historically in early space nations, universities have played a large role in developing technical capacity and even prototypes or full satellite missions thanks to modular, versatile 10cm x 10cm CubeSat designs first popularized at CalPoly and Stanford universities.[xlvii,xlviii] CubeSats reduce the barriers to entry for new satellite developers by minimizing the amount of parts needing to be fabricated as standard, well-tested parts are available, and CubseSats have adopted uniform electrical and mechanical standards, which simplifies the design process and integration-ability with existing subsystems.[xlix] Organizations like NASA have published open standards for launch requirements and testing, and these typically are used for guidance on testing parameters and best-practices.[l] University involvement in satellite development is highlighted by the BIRDS-Program of Kyushu Institute of Technology and JAXA aimed at training satellite engineers from developing nations. In partnership with universities in Africa, Asia, and South America, BIRDS has directly contributed to the launch of numerous CubeSats through training of students from non-traditional space nations and has also resulted in the first satellite launch of Ghana (GhanaSat-1) with All Nations University and a Nigerian nano-satellite (Nigeria EduSat-1) with Federal University of Technology Akure.[li] Plans for the fifth-generation BIRDS-5 Program will see both Uganda and Zimbabwe build and launch their first respective national satellites.

However, less robust and long-lasting missions tend to result from CubeSat development. In the short-term the satellites do no help significantly with data provision. Over a long timescale, the capacity-budling element will come to bear more weight. We have identified a 'learning vs performance' trade-off for satellite projects. Particularly in emerging space nations that often influences the decision to involve donors or foreign partners in satellite development projects.[lii]

Satellite Size Classes are Associated with Archetypes of Satellite Development

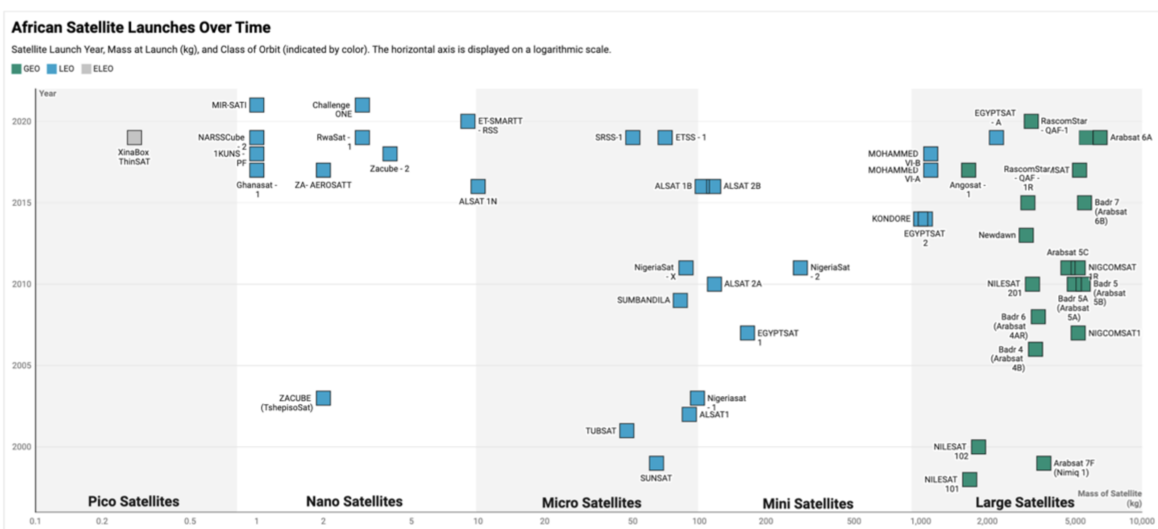


Figure 3-8: Satellite Size Classes Vs. Year of Launch

Lessons from the Brazilian experience have shown the benefit of space activities in developing robust human capital and also that partnerships with local universities (ex. Technological Institute of Aeronautics) and foreign partners (ex. China National Space Administration) are critical to technical advancement in national capability like development of highly reliable earth observation satellites, i.e., the China–Brazil Earth Resources Satellite (CBERS) program.[liii] The experience of South Africa emphasized the development of local capacity and training of university students at different levels, where the University of Stellenbosch took a lead role in developing low-earth orbit (LEO) satellite designs leading to the launch of SunSat1 (or Stellenbosch UNiversity SATellite) in 1999 which helped train over 100 engineers between 1992 and 2001.[liv] Additional survey data from Woldai 2020 identifies the most active universities and departments in African nations teaching degree-granting courses on earth observation and remote sensing.[lv] To increase human capital, nations have also instituted incentive structures to reabsorb experts from their own diaspora including Ethiopia, Ghana, and Rwanda to assist in space or remote sensing implementations.[lvi]

3.7.3 Additional Regional Coordination Is Needed to Maximize Benefit from African Earth-Observing Satellite Missions

Low level of coordination between regional space actors in Africa currently exists. As is evidenced by the stalling of the African Resource Management Constellation (ARMC) project first proposed in 2002, large technical collaborations are susceptible to significant delays and vulnerabilities. Of the four nations agreeing to participate – Nigeria, Algeria, Kenya, and South Africa – only Nigeria has successfully launched an EO satellite mission, NigeriaSat-2 in 2011, towards the constellation. The mission has effectively reached its end of useful life and still none of the other constituent nations has established strong launch plans. The value of such a constellation would be immense, particularly if data-sharing efforts were then coordinated and data made easily available to practitioners on the continent. It is strongly recommended that open sharing be standardized regionally and resources be allocated to the continual upkeep of platforms and services supporting these efforts.

3.7.4 The African Space Agency will Have a Large Role in Charting Space Policy for the Region

The legal and space policy involvement of most African nations is relatively weak compared to the rest of the world. Outer space is regulated by five main legal treaties: The Outer Space Treaty of 1967, The Rescue Agreement of 1968, the Liability Convention of 1972, the Registration Convention of 1976, and the Moon Agreement of 1984. Of African nations, 53% have signed or ratified the Outer Space Treaty of 1967, the most foundational of the legal space agreements.[lvii] This rate is lower for other space treaties. The African Space Agency will have a key future role in progressing space policy for African nations, which may include wider adoption of international agreements by individual nations but also could include development of region-specific policy for general space policy, earth observation data-sharing, launch site development, or space spin-offs.

3.8 Conclusions

There has been a proliferation of satellite design, build, & launch activity from African nations. Many nations actively recognize the benefit of national space programs in achieving their domestic agendas and the AU Agenda 2063 goals for sustainable development. Another important development is the appearance of new satellite project archetypes in African nations.

Tunisia's Challenge-One is a unique archetype for early satellite nations both in its local design, build, and manufacturing process and in its successful reliance on the local commercial sector. Evidence suggests that many space nations in Africa are heading in a similar direction with Ethiopia and Nigeria also announcing plans to build manufacturing capabilities in-house. Increasingly larger budgets are being allocated to African space agencies from their own national governments. Successive years have seen many countries' operating budgets grow significantly, though recessions and shocks to foreign currency exchange rates have negatively affected several countries such as Angola and Nigeria. In addition, the establishment of the regional African Space Agency hub is a positive sign for overall space budget allocation on the continent as it creates a centralized budget mechanism and new sense of initiative for cross-country collaboration and project development. The African Space Agency is also expected to have an important role in negotiating space policy affairs both within and on behalf of Africa nations with regards to aspects like orbit space designation and open data standards, for example.

Partnerships in international and regional respects are emergent and growing in relevance. In particular, China, Russia, Japan, and the European Union are active on the African continent with limited direct involvement from American agencies such as NASA. Regional African collaborations are growing, as well. For example, the Egyptian Space Agency has proposed the African Development Satellite Initiative (AfDev-Sat) with input from Botswana, Ghana, Kenya, Morocco, Nigeria, Uganda, and Sudan to build engineering capacity across the region by providing hands-on training and assembling a novel CubeSat. There is a marked growth in nanosatellite launches spurred by the popularity and modular nature of CubeSat designs. CubeSats are readily adaptable to the design specifications of different nations and ideal as design prototypes for newly attempted mission types. A number of first national satellite projects in Africa are CubeSats (Mauritius's MIR-SAT1, Kenya's 1KUNS-PF, Ghana's GhanaSat-1, Tunisia's Challenge-One), and several planned launches from entrant nascent space nations are also expected to be CubeSats (Zimbabwe, Uganda, Djibouti, Burkina Faso, Botswana). Many unlaunched CubeSat projects (KN-SAT1 University of Khartoum in Sudan, ERPSat-1 Sfax School of Engineering in Tunisia, ET-SAT Addis Ababa Institute of Technology) have also served as important learning projects for technical capacity-building. Potential drawbacks to this increased space activity in Africa include environmental emissions from satellite launches, growth in the space debris challenge, continued dependence on external launch sites, and general inaccessibility or public data-sharing mechanism for new missions, limiting benefit to the general public and independent scientists and organizations across Africa. Data sharing policies must be developed to maximize the use of satellite earth observation data in particular.

Chapter 4

Case Study of Satellite Remote Sensing Applications in East Africa:
Assessing Water Futures and Determining Localized Effects of Climate-Influenced Mobility Pressures

4.1 Introduction

In this chapter, a demonstration of applying novel satellite methods from the previous sections in a detailed case study is explored. The potential of third order satellite effects is vast and among the most flexible and ripe for innovation from the classifications identified. This is because third order effects are naturally diverse and tend to bring together different disciplines and schools of thought around problem-solving. New combinations of datasets and analysis methods create an increasing number of permutations and network effects. Here, the conceived methodology combines a unique African urban population dataset with groundwater analysis from the NASA GRACE satellites. This study also especially makes extensive use of geospatial data and satellite remote sensing data to supplement, build, and collect robust datasets with which to work. New insights around climate-influenced mobility patterns are revealed at localized scale that was previously poorly studied and quantified.

4.2 Research Question

In this study, I aim to answer two main research questions. First, how do different factors such as climate change, human-environment-interaction, mobility, and water source dependencies influence water futures in East Africa? And second, what effect – if any – is had on climate-influenced migration pressures?

4.3 Study Area

There are ten study countries in East Africa that were analyzed in this work: Chad, Djibouti, Egypt, Ethiopia, Eritrea, Kenya, Somalia, Sudan, South Sudan, and Uganda. These countries were chosen because of their relevance to the region, as well as because of their unique makeup in overall climate, level of water stress, geography, size, and respective histories. Water is a critical resource, with available freshwater supplies making up less than 1% of the total water mass present on Earth. Of this percentage, humans make use of a portion for everything from industrial processes to drinking and bathing water to irrigation for vast crop lands, and more. Changes in Earth's atmospheric warming due to anthropogenic impacts are altering the water cycle significantly, as well as weather patterns because of complex systems effects of higher energy (or warmer) water vapor droplets contributing to stronger storms, more prolonged drought seasons, intense wet and dry seasons, and more drastic El Niño and La Niña cycles.[lviii] In particular, East Africa is a region which is expected to be heavy impacted by the physical effects of climate change and is also home to many vulnerable populations which greatly compounds risk levels.

Study Countries: East Africa
Chad
Djibouti
Egypt
Ethiopia
Eritrea
Kenya
Sudan
South Sudan
Somalia
Uganda

Table 4.1: Study Countries in East Africa

4.4 Methodology

The methodology of the study is carried out at the urban or city-level scale using the Africapolis dataset as a reference point.[lix] Africapolis contains rich spatial and tabular data for cities on the African continent above 10,000 residents in population. This is important because in many African countries, the majority of urban citizens live in small to medium-sized cities rather than in large metropolises. However, metropolises tend to be most often studied and represented in the data as they are more visible. Access to critical data sources and institutional partners in metropolises can be also more straightforward to secure in many cases. In this regard, satellite data plays a critical role. Its ability to be collected and analyzed with high frequency over wide, remote geographic areas is unparalleled even by peer technologies like ground-based sensor networks or drones which are limited in range, can require site access and permits, and which need more frequent maintenance and/or constant redeployment. The study introduces a conceptual framework for additional risk factors affecting water futures. These are more granular analysis dimensions related to climate, water resources, mobility, and water usage trends which are resolved at the city-level scale. The conceptual framework branches presented may be used to isolate different water and sustainability-related issues of choice or utilized together to categorize a full water future scenario.

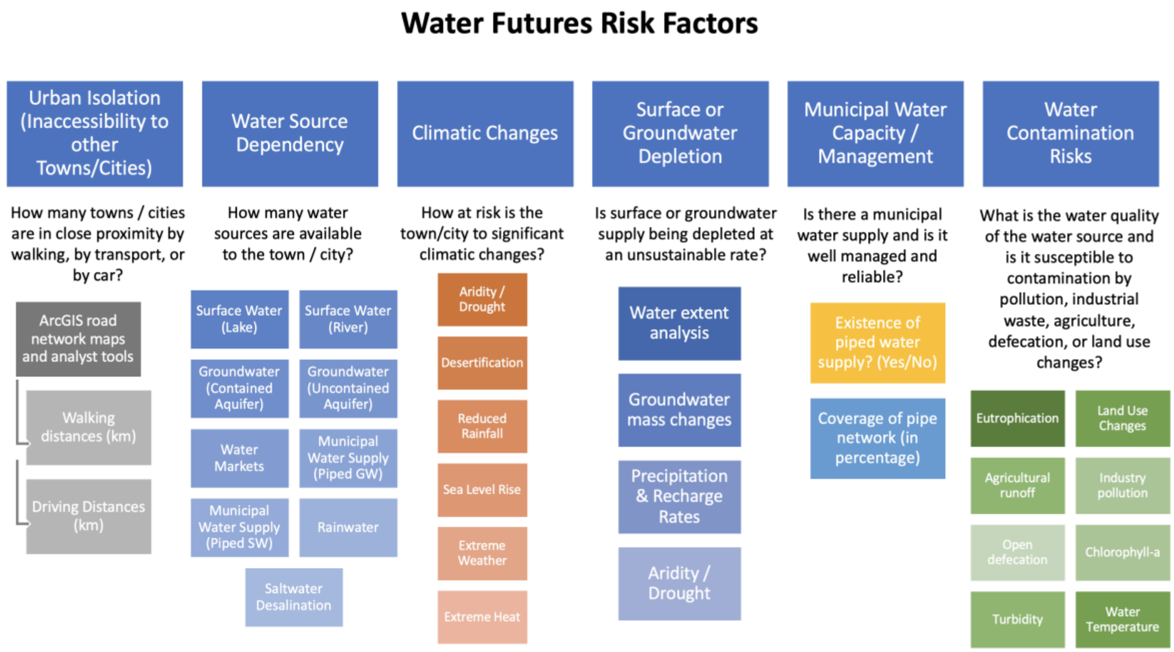


Figure 4-1: Water Futures Methodology Diagram

Lastly, the study draws from the econometric toolkit of casual inference to attempt to better understand population growth rate shifts between cities within the same country and in neighboring countries. Research has shown that much climate-related mobility patterns can be observed at the local scale.[lx] This research aims to address these regional and local scale-level effects. A predictive LASSO model is utilized to perform feature selection from among many variable categories covering locator variables, population variables, built-environment variables, water variables, livelihood variables, climatic variables, human-environment variables, and mobility variables. This dataset was built and cleaned through a painstaking process that involved assembling, converting, and resolving data from many different sources. Satellite-derived data inputs and GIS shapefiles were utilized where relevant for insights such as groundwater variability, surface water extent, particulate matter concentrations, tree cover loss, and night light change over time. For processing, spatial polygon data was rasterized at 0.01 grid cell sizes and attributed as feature data rows where overlaps with cities' urban latitude-longitude coordinates from the Africapolis dataset were observed and combined in a tabular form. Administrative boundaries were used where applicable and necessary at the admin levels 1,2, and 3 for all available countries. The final study dataset features 2,387 total datapoints (rows) of unique urban cities above 10,000 people in population as of 2015. The final assembled tabular data also has 76 features of dimensionality (columns) in total describing many explanatory variables for population change, for example, built-environment index, precipitation changes, food insecurity, GDP change, livestock conditions, land cover change, and biomass decline. Details of the assembled data layers and processing will be further described. The statistical analysis was done in Stata and R Studio using psych and glmnet libraries.

4.5. Data Layers

4.5.1 Africapolis Dataset

The Africapolis dataset is among the most complete population map datasets for Africa. In order to analyze and work with the Africapolis dataset, the shapefile polygon layer was processed in ArcGIS and resolved to XY-point locations at the centroid of the town locations. They were matched using ArcGIS' locator function by city name, which matched over 95% of cities in the target country datasets. The remaining points were resolved manually, and discrepancies were mainly due to subtle spelling differences that were varied between transliteration methods. The feature rows were then filtered by 2015 population (the most recent population year count in the dataset), and any observations with populations below 10,000 people were eliminated. The study country bounds were clipped to the admin level-0 national shapefiles. This clip extent was used consistently throughout the study for continuity and accuracy.

The category of urban population size was of particular interest in order to help understand the differing dynamics and pressures on small towns or cities versus large cities or urban metropolises. An urban classification size index was created, splitting the cities into four distinct population size categories. Small cities ranged from 10,000 in population to 50,000. Medium-sized cities ranged from 50,000 to 100,000 in population. Large cities had populations between 100,000 and 1 million inhabitants. Biggest cities were those over 1 million in population as of 2015. These size classifications were used consistently as definitions and target GIS layers in this study. A descriptive table of the urban size breakdowns is shown below.

Categories of Urban Population Size		Class	Description
10,000	50,000	**Small**	Towns
50,000	100,000	**Medium**	Towns/Cities
100,000	1,000,000	**Large**	Cities
1,000,000	Above	**Biggest**	Metropolises

Table 4.2: Urban Categories Breakdown

Spatially, the cities and towns are distributed with the biggest metropolises tending to aggregate in Egypt, Ethiopia, and Uganda. Significant population numbers are found along the Nile River delta and flood plain throughout Egypt and Sudan. In addition, population numbers in various coastal areas, in the Ethiopian highlands, in the Lake Victoria watershed bounds, and along the Chad-Sudan Sahel also represent significant clusters in population density.

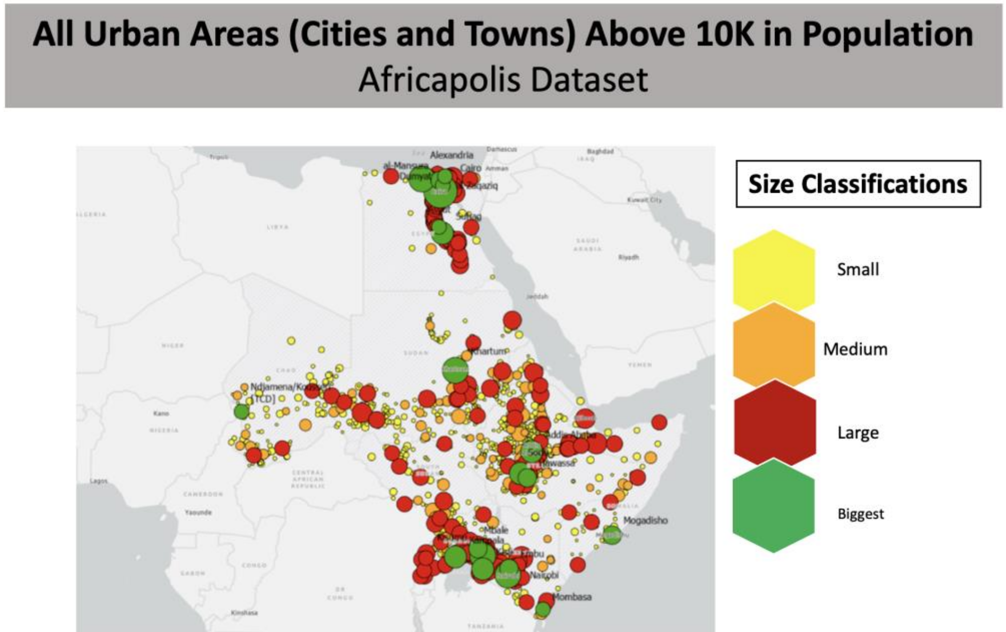


Figure 4-2: Urban Area Spatial Distribution by Size

The majority of cities by count are small (10k-50k population), making up 1,949 of 2,387 total datapoints. They are followed by medium cities (229), large cities (189), and then biggest cities (20 metropolises). Illustrating the importance of focus on a broad array of urban size classes, we find that the percentage of the urban population living in small and medium size cities make up the majority of the urban population in three separate study countries: Eritrea, South Sudan, and Chad. In half of the study countries, the percentage of the urban population living in large cities (100k – 1 million people) is over one-third of the total urban population. These countries are Djibouti, Eritrea, Somalia, South Sudan, and Uganda. Only one country (Kenya) has the majority of its urban population in 'biggest' cities, or metropolises, at approximately 62% of the urban population in 2015. Egypt and Uganda are also nations whose urban populations are significantly skewed towards large urban agglomerations. Sudan has the most evenly distributed population spread across the four urban size categories, followed by Eritrea (with the exception of 'biggest' cities of which it has none). Summary statistics are visualized in the figure below.

Count of Cities by Population Breakdown

Summary Statistics	Small	Medium	Large	Biggest
Number of Cities	1949	229	189	20
Average Population	21,414	70,119	236,606	3,938,568
Total Cumulative Population	41,734,934	16,057,281	44,718,601	78,771,363

Table 4.3: Count of Cities by Population Breakdown

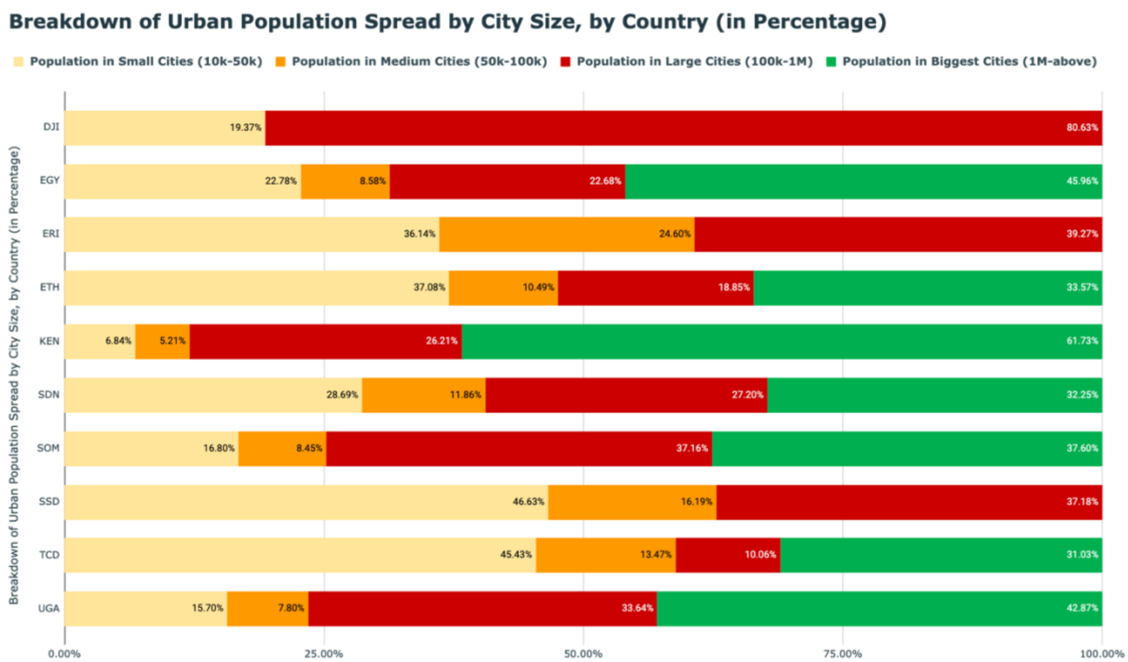


Figure 4-3: Breakdown of Urban Population Spread by City Size, by Country

4.5.2 GLDAS v2.2 Groundwater Storage Analysis

Groundwater analysis was done with Giovanni GLDAS (Global Land Data Assimilation Model) v2.2 which integrates GRACE and GRACE-FO data directly.[lxi] Princeton Meteorological forcing is used in the processing. Groundwater storage depth values in mm are spatially and temporal explicit. Note that color scales for the maps by country each have different color scales. The following equation for terrestrial water storage (TWS) was used:

Using NASA GRACE & GRACE-FO Data for Groundwater Change Analysis:

$$P - ET - Q = \Delta TWS$$

$$\Delta TWS = \Delta GW + \Delta SM + \Delta SWE + \Delta SW$$

$$\Delta GW = \Delta TWS - \Delta SM - \Delta SWE - \Delta SW$$

Where P = precipitation, ET = evapotranspiration, Q = Runoff, TWS = Terrestrial Water Storage, GW = Groundwater, SM = Soil Moisture, SW = Surface Water, SWE = Snow Water Equivalent

Groundwater values are traditionally challenging to measure given limitations of often-utilized calculation techniques. Advances in satellite remote sensing techniques through gravitational variations measured aboard the NASA GRACE (Gravity Recovery and Climate Experiment) satellite have provided the most accurate picture of groundwater mass changes and total water terrestrial water changes to date, since the first mission began operating in 2002.[lxii] Uganda by far is endowed with the most groundwater resources on average. Arid, desert countries like Egypt, Djibouti, and Sudan rank among the bottom.

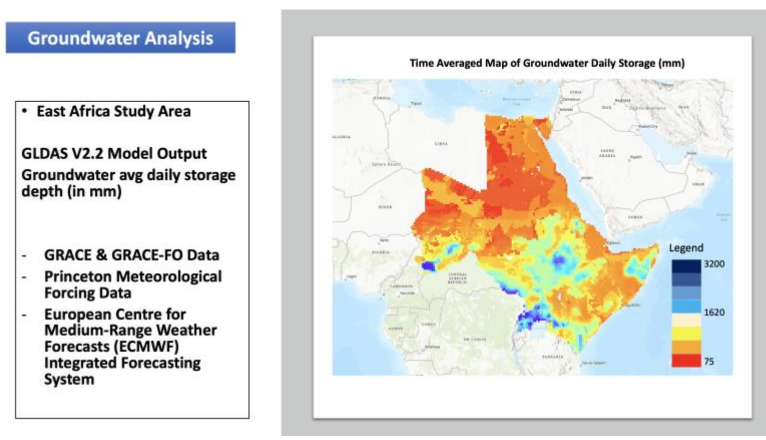


Figure 4-4: Groundwater Analysis Map, Study Area

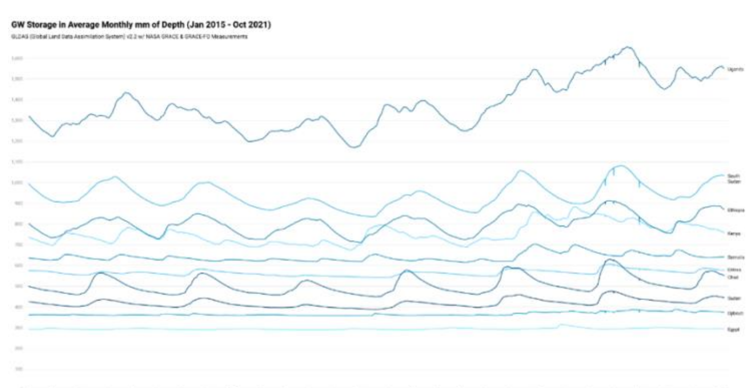


Figure 4-5: Groundwater Analysis Chart, Study Area

The countries exhibit high variability in natural water storage levels in respective basins. Note that figures disaggregated by country have different scale values. Regions of Chad show water storage values orders of magnitude greater than peer countries.

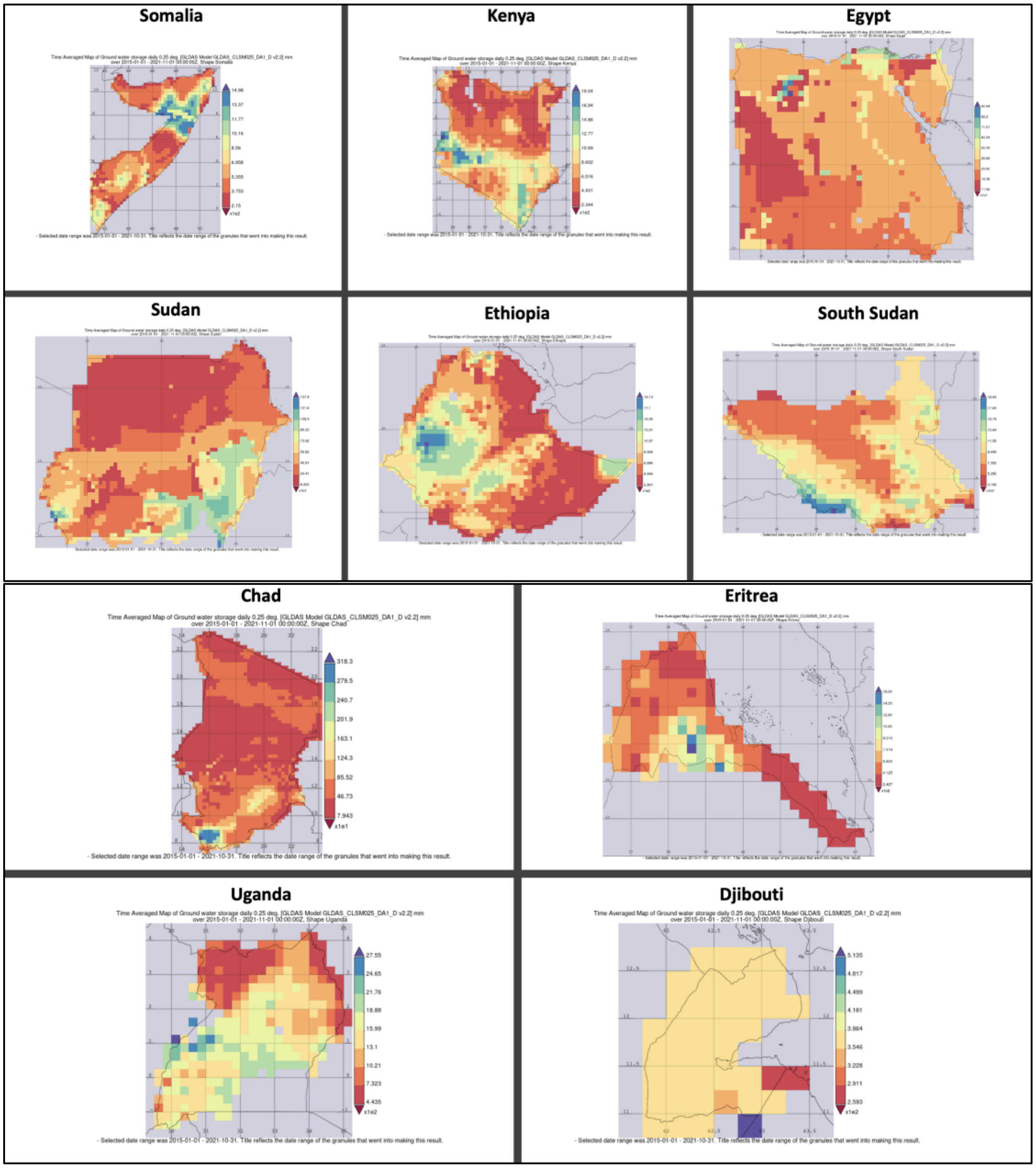


Figure 4-6: Groundwater Analysis, by Country

4.5.3 ArcGIS Network Analyzer Mobility Analysis

Analysis in ArcGIS was done using the city locations as nodes in the Network Analyzer Tool. Travel distances using the ArcGIS base map road layer gave standard resolution polygons of real travel distance extent based on terrain friction. Values in the table below detail the driving and walking distance polygons generated for each city size class.

Mobility Analysis -- Distances Analyzed			
By City Size Classes			
Small	Medium	Large	Biggest
Walking			
5 km			
10 km			
Driving	Driving		
20 km	20 km	Driving	
30km	30 km	30 km	
	60 km	60 km	
	90 km	90 km	Driving
	120 km	120 km	120km
			240km

Table 4.4: Mobility Analysis, Distances Computed

Differential mobility patterns were observed. The accessibility of different cities and towns to other regions varies widely. The figures below show the different archetypal patterns found throughout the study region for small and medium cities. Some cities are marginally accessible to other cities, and others are disconnected altogether.

Different Observed Mobility Patterns
Small Cites (10k – 50K) Ranging from Least to Most Connected

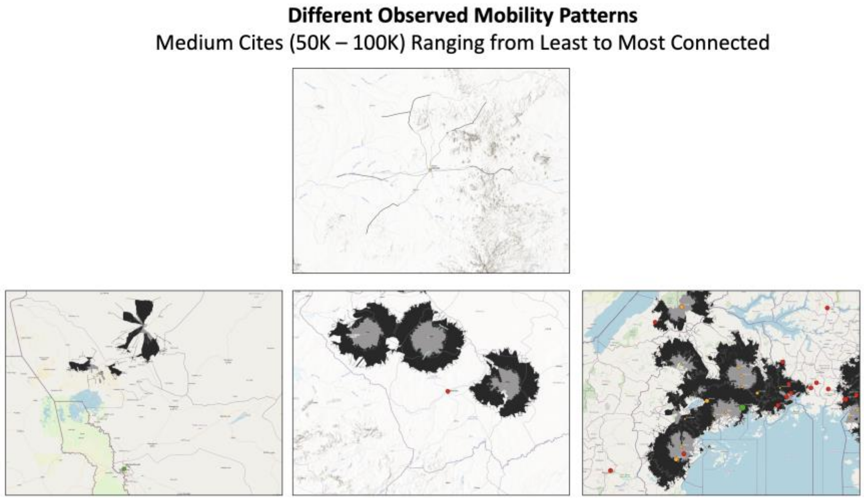


Figure 4-7: Mobility Patterns for Select Small and Medium Cities

Connectivity to metropolises was measured in the inverse. The heatmap below was generated by overlapping the travel distance polygons from small, medium, and large cities in order to show how accessibility metropolises are to other urban areas. In other words, how accessible are metropolises to inflows from surrounding areas. As can be seen, Cairo is one of the most well-connected megacities on the continent. Kampala and Khartoum have modest connectivity values with surrounding areas.

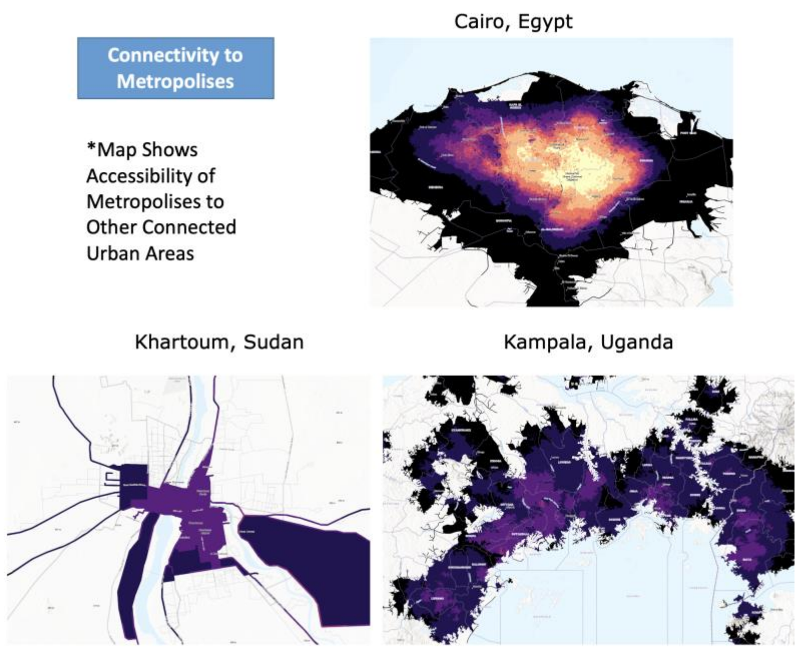


Figure 4-8: Mobility Patterns for Select Biggest Cites

4.5.4 Climatic Map Layers from World Desertification Atlas

Lastly, climatic map layers were processed from the World Desertification Atlas.[lxiii] These included saltwater intrusion levels, aridity, aquifer depletion rates from NASA GRACE, land degradation, livestock and irrigation levels, low rainfall, and agricultural throughput. The climatic layers are instructive in categorizing compound risks facing respective cities. A sample of the data layers visualized is given below.

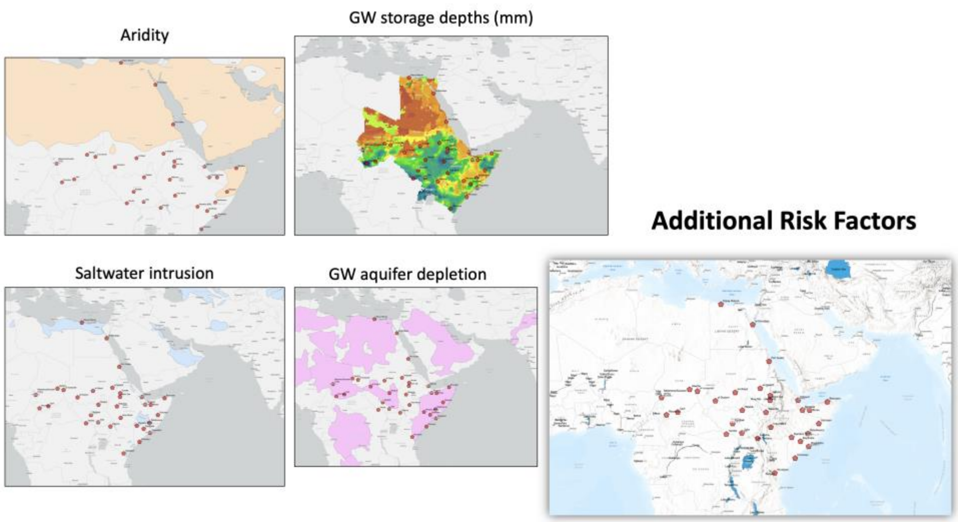


Figure 4-9: Climatic Layers as Risk Factors

4.6 Results

In summary, the data was tested for urban isolation and groundwater dependency. These are hypothesized as exacerbating risk levels one and two. Then additional land pressures, water quality issues, and adverse climatic variables were considered as additional stressors. At this first level of abstraction, analysis was done visually. Here we reiterate our hypothesis that cities that are more isolated are more susceptible to water and climate shocks generally. The results are presented in the following section.

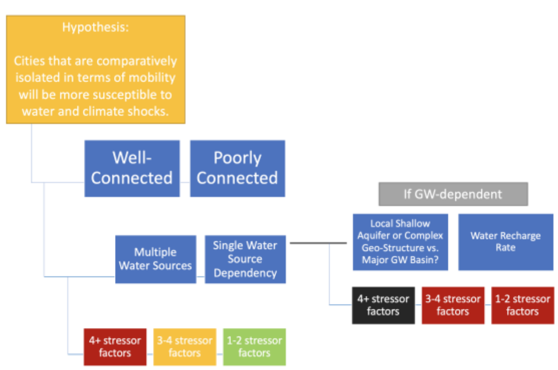


Figure 4-10: Hypothesis Test

4.6.1 Relatively Isolated Large Cities are the Most at Risk to Adverse Water Futures

Relatively isolated urban cities were first identified through the mobility analysis. The study identified a number of large (100k -1 million residents) urban areas which are located more than 90km from the nearest urban area of any size. Of these cities 11 are groundwater dependent as their main water sources, as was determined through satellite analysis. Of those 11 cities, two face four or more additional pressures or water stressors: Sarh, Chad, and Hargeisa, Somalia. Six cities face three stressors: They are Al-Duaiym, Sudan; al-Qadarif, Sudan; Baledweyne, Somalia; Galcaayoo, Somalia; Burao, Somalia; and Rumbek, South Sudan. These cities in particular will be susceptible to drought effects, extreme heat, and El Niño seasonality. This methodology offers a low-fidelity means to understand water futures at an urban-level scale with little data inputs. We will test this same hypothesis further through quantification methods.

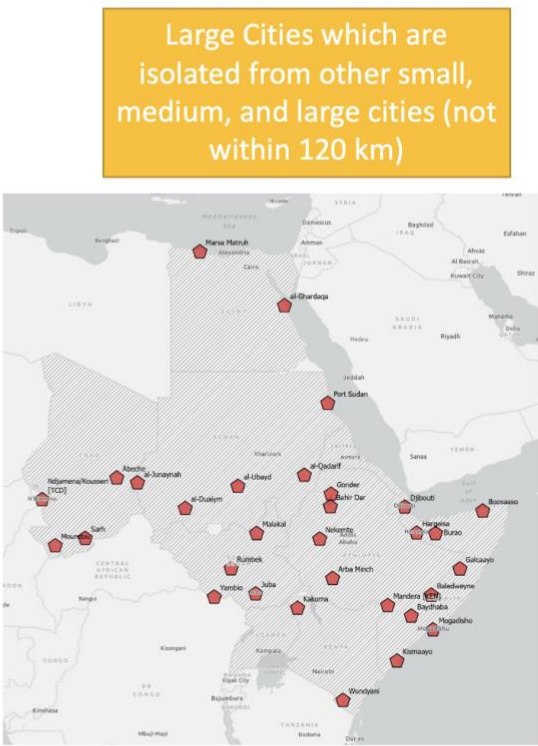


Figure 4-11: Large, Relatively Isolated Cities

Relatively Isolated Large Cities (Not accessible to small, medium, large urban areas within 120 km)	
agglosName	**ISO3**
Abeche	TCD
Sarh	TCD
Moundou*	TCD
Ndjamena/Kousseri [TCD]	TCD
Rumbek	SSD
Juba	SSD
Malakal	SSD
Yambio	SSD
Hargeisa*	SOM
Kismaayo	SOM
Boosaaso	SOM
Baydhaba	SOM
Burao	SOM
Galcaayo	SOM
Baledweyne*	SOM
Mogadisho	SOM
Djibouti	DJI
Marsa Matruh	EGY
al-Ghardaqa	EGY
Port Sudan	SDN
al-Qadarif	SDN
al-Duaiym	SDN
al-Junaynah	SDN
al-Ubayd	SDN
Kakuma	KEN
Mandera [KEN]	KEN
Wundyani	KEN
Gonder	ETH
Bahir Dar	ETH
Arba Minch	ETH
Nekemte	ETH
*Highlighted cities are accessible to another large urban area between 90 - 120km away	

Table 4.5: Large, Relatively Isolated Cities

4.6.2 LASSO Regression Results Detect El Niño Effects and Longitudinal Migration

Now, we use population change rate from 2010-2015 as the dependent variable in a LASSO regression. Population dynamics are important indicators for climate trends and human-environment-livelihood factors. Local inflow and outflow migration patterns can reveal aspects of climate or water-related stressors. As such, we analyze population growth rate as a key proxy for intra-country and intra-region mobility patterns. In most cases, population trends upwards as would be commonly expected in most areas, but the dataset does feature a number of observations that show negative population growth, or population decline.

In this step, the data layers were increased to high-fidelity levels with 76 unique data columns. This expanded dataset included new variables like annual temperature and precipitation from NCAR, annual GDP levels measured as percent changes, urban accessibility travel times, and food insecurity levels from the Famine Early Warning System.[lxiv] LASSO regressions are predictive and capable of robust feature selection from among many variables. This is why we have expanded our dataset to attempt to reduce chances of overfitting, and we can test if the hypothesis presented above in the low fidelity scenario is valid.

Dataset Features

Locator Variables	City Name	**Climatic Variables**	Low Rainfall
	Country		Aridity
	Latitude		Fire Incidence
	Longitude		Land Surface Temperatures
Population Variables	Population Growth Rates		Precipitation
	City Size Class		Precipitation Change
	New City Index		Temperature
	Spatial Population Density		Temperature Change
Built-Environment Variables	Metropolitan Classification	**Human-Environment Variables**	PM 2.5
	Built-up Index		Terrestrial Modification (Land Cover Change)
	Night Light Change		Low Throughput Agriculture
Water Variables	Freshwater availability		Irrigation Area
	Groundwater Depletion		Tree Cover Loss
	River Proximity		Land Productivity Decline (Nitrogen)
	Lake Proximity		Biomass Decline
	Groundwater Storage		Livestock Area
	Groundwater Aquifer Type		Human-induced Water Stress
	Groundwater Recharge Rate	**Mobility Variables**	Accessibility to Cities
Livelihood Variables	GDP Change		Mobility Overlap Regions
	Food Insecurity		Isolated Cities
	Infant Mortality		Voronoi Index

Table 4.6: Full Dataset Features

Correlation values for a sample of continuous variables in the dataset describes collinearity levels in data values. As we would expect, some variables are reasonably correlated, particularly climate-related variables to each other and livelihood variables to each other, as well. The LASSO regression is capable of feature selection and will reduce poorly correlated predictor variables to zero in the output model.

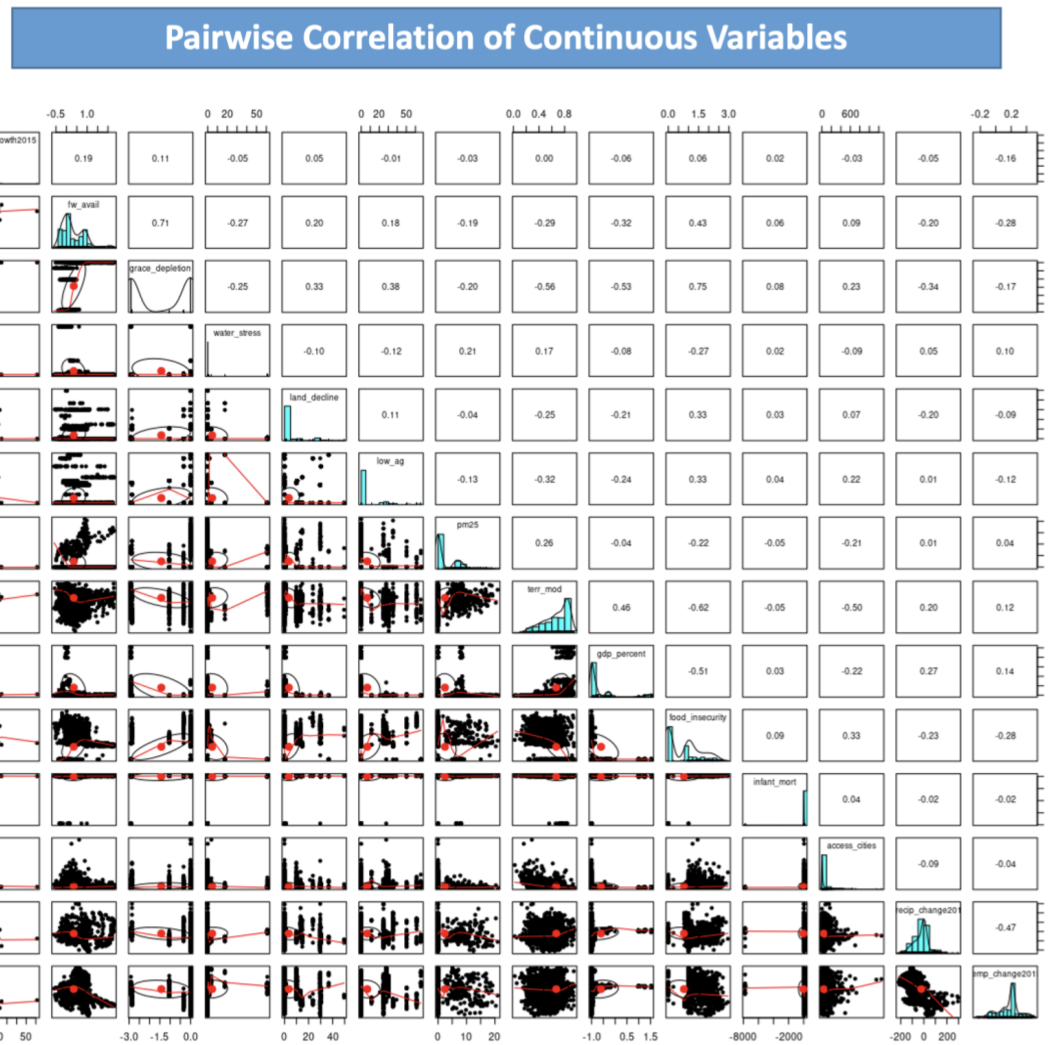


Figure 4-12: Pairwise Correlation Values for Continuous Variables

Output results from two runs of the predictive regression models are shown below. Both have relatively low R squared values, so the predictive power is quite low as a model. However, the results still have explanatory value, given the diverse and many overall factors – even water and climate unrelated – that can feasibly be contributing to population growth or mobility. The significant variables identified in the first run when all dataset variables were included are identified in Figure 4-14. Validating the low-fidelity results from the previous step, we find that the model identifies urban isolation as a key variable. This is consistent with our previous results. Also, annual temperature in 2015, particulate matter 2.5, aridity, and longitude are found to be significant. This corresponds to the large El Niño cycle that affected East Africa in that year.[lxv] El Niño has significant effects on agriculture, flooding, soil moisture, and economic losses during its cycles.[lxvi] Its effects on climate-based mobility, and micro-mobility in particular, has previously not been well-studied, so this is a very significant finding. Also, the longitudinal dimension of the migration patterns is unique. It suggests that populations are moving north to south rather than east to west in response to El Niño climate pressures in the region. This has important implications in urban planning and governmental planning approaches. It also may give insight into who exactly is moving, as we know that may large populations in the region live in clusters around major river basins such as the Nile. It is possible that these populations are moving longitudinally in response to climate-driven flooding effects or agricultural losses. Climate in the region is also more variable along a north-south axis in general, so motivation to move to more suitable climates (lowlands and highlands in Ethiopia, for example) may be more detectable for this reason. Suggestions for future work and investigation are to study these effects by country and by urban size class to identify differences in these populations. The methodology is reproducible and can be applied to any region in the world given sufficient data inputs.

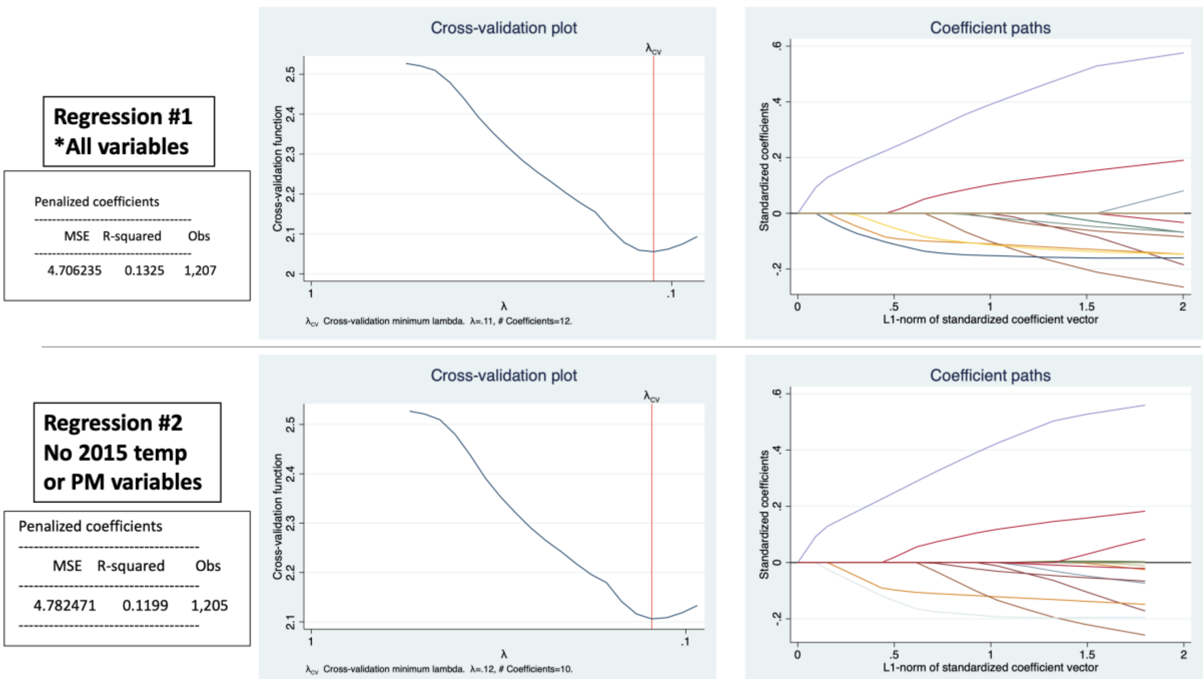


Figure 4-13: Regression Results for Case One and Two

Regression #1 *Including all Variables
Selected Variables of Interest by LASSO
• popgrowth2010
• smallcity
• largecity
• biggestcity
• metro
• pop_density
• arid
• pm25
• isolated_cities
• temp_change2015
• temp2015
• longitude

Regression #2 *Excluding PM2.5 & 2015 Temp
Selected Variables of Interest by LASSO
• popgrowth2010
• smallcity
• largecity
• biggestcity
• metro
• pop_density
• gw_storage
• arid
• Lstmax_day
• temp2014

Figure 4-14: Feature Selection from LASSO Regression

4.6.3 Groundwater Storage, Aridity, and Temperature Have Strongest Effect of Intraregional Migration

Using results of regression run #2, where 2015 specific variables were excluded (such as annual temperature in 2015 and PM 2.5 in 20150, we are able to identify trends in more average weather years than the cycles affected by El Niño. These results are more generalizable in terms of their representation of climate effects in a typical year. Interestingly, we see that temperature still has a strong predictive value, as does groundwater storage indicators from the GLDAS and GRACE analysis, aridity, maximum land surface temperature in the summer, and urban size class. The East Africa region is experiencing extreme heat increase due to climate change that is likely to increase further and exacerbate climate-based migration and other pressures on livelihood, agriculture, and water. Arid areas that are most susceptible to drought will also see many negative impacts. The results show that groundwater storage is a major factor in micro-mobility, and this is likely further reinforced by urban size class. Many smaller cities are dependent on groundwater as a main source and also more likely to become vulnerable to water stress when drought, irrigation, water overdraft, and extreme heat increase. Many small cities also have no municipal water supply and are using unimproved water sources or wells for daily uses. These findings suggest that groundwater monitoring through NASA GRACE measurements, supplemented by temperature data, humidity data, and drought monitoring could have a large impact on forecasting mobility patterns and easing hardships for vulnerable populations affected by these trends. Applied policy recommendations will be presented in the following section.

Chapter 5

Policy Insights in the Context of the 2015 Paris Agreement

5.1 Background

The 2015 Paris Agreement has many dimensions of interest and relevance.[lxvii] Most attention is typically paid to the flagship NDCs (Nationally Determined Contributions) framework. Beyond this element, there are several nuances of the Paris Agreement that warrant further investigation and improvement. Several articles of the Paris Agreement are particularly notable to address during this discussion. First, approaches to mitigation and adaptation are a main focus. The explicit reference to equity noted in Article 2 is relevant in reference to low-emitting African nations, who also have the most vulnerability to negative climate change effects. Second, historically global climate roles have been shaped by powerful international dynamics. This is codified in Article 3, which addresses 'common but differentiated responsibilities.' It can also be looked at through the lens of nationally determined contributions (NDCs) per Article 4, which have been widely covered in literature. We also explore Article 8 which recognizes the importance of averting and minimizing losses and damages associated with climate change and supports enforcement of the Warsaw Mechanism. Insights from the previous case study section also have particular relevance to the Warsaw Loss and Damage Mechanism regarding the risks associated with slow onset events and the effects of climate-forced mobility. A contextual analysis review was conducted to draw insights and areas of improvement from the above listed policy mechanisms. From this, two main suggestions for improvement are given along different policy dimensions.

2015 Paris Agreement Contextual Analysis			Thematic Areas
Article 2	Inequality Due to Climate Change	*Inequities in Emissions & Vulnerabilities*	Inequity in Emissions
Article 3	Comparative View Between Nations	*Special Considerations between Nations*	Inequity in Emissions & Risk Profile, Adaptation & Mitigation
Article 4	Debate on Efficacy of National Pledges	*Nationally Determined Contributions*	Inequity in Emissions
Article 8	Loss & Damage: Warsaw Mechanism	*Loss & Damage Due to Climate*	Loss Recovery
Article 9	Climate Finance, Externalities	*Climate Financing Mechanisms*	Adaptation & Mitigation

Table 5.1: 2015 Paris Agreement Contextual Analysis

5.2 Suggested Climate Policy Improvements

5.2.1 Acknowledging Inequities due to Climate Change in a Robust Manner

It is important in a rhetorical and practical sense to develop more nuanced approaches to discussing varying effects and responsibility around climate change. It is well established that some nations are far higher emitters than others and are responsible for large shares of climate emissions worldwide. In the context of the Paris Agreement this is mainly addressed through the dichotomy of ‘developed and developing’ nations, as well as particular attention given to small-island states. The Paris Agreement also addresses vulnerable populations independent of nation-states.

Arguably, nations should also be classified as high and low-emitters, in objective terms. Risk profiles differ greatly between nations. Though many nations have had little overall effect on present warming patterns, they are subject to the same climate risks. A classification system is developed and presented here to address this gap using indicators for emissions and for natural hazard risks. The INFORM Global Risk Index is a global dataset that identifies and characterizes nations that are at high risk of natural disaster or humanitarian crisis around the world.[lxviii] The natural hazards parameter includes risk levels for damage due to floods, tsunamis, earthquakes, tropical cyclones, and drought. These are aggregated into a cumulative risk score and associated risk class. This data was cross-compared with emissions data from 2019 for each nation. After calculating mean and median values of emissions, four risk quadrants were created. There are nations with high risk of disaster who are either high emitters or low emitters, and there are nations with low levels of risk who are similarly either high or low emitters. In particular, the high risk-low emitter category of nations is of concern. Though these countries contribute the least to global climate change, they stand to be the most impacted in the years going forward. The Paris Agreement’s current mechanisms for addressing these inequities are insufficient and must be improved in future climate policy. More robust mechanisms for understanding future pressures in high risk-low emitting nations in particular should applied.

Figure 5-1: Natural Risk Quadrants, by Total and Per-Capita Emissions

5.2.2 Accelerating Action to Implement the Warsaw Loss & Damage Mechanism

Insights on climate-influenced migration patterns from the previous study are particularly relevant in the case of the Warsaw Mechanism. The Warsaw Loss & Damage Mechanism addresses a critical, under-addressed area of climate change effects which is losses that have already been incurred or that will inevitably occur due to levels of warming that have already been reached. This is especially pertinent to African nations and to many low-emitting nations who are nonetheless very vulnerable to climate hazards. The Warsaw Mechanism has a number of functions which are important to highlight: (1) the development of a task force for displaced persons due to climate change to make recommendations, (2) the establishment of a clearing house to connect risk management experts to the end-users who are the intended recipients, and (3) a mandate to enhance support (financial, technology transfer, capacity-building, etc.) to address loss and damage.

For low-emitting African nations, it is imperative that the Warsaw Mechanism be able to fulfill its functions towards an equitable, unified approach of combating global climate change. It is one of the only mechanisms created solely for the purpose of providing this essential buffer for nations experiencing the worst effects of climate change. But the Warsaw Mechanism does not include any form of obligation for countries to actually move towards actions, and due to this laxity, no little concrete steps have been moved forward. Most discussions are centered are task force work and research to determine how to define loss and damage, as well as some attention given to funding. At the current stage, there are two aspects of the policy that are notable. First, defining what qualifies as a climate-related loss and second developing tools to mitigate the financial and risk burdens associated.[lxix] In particular, climate-related losses can be difficult to attribute due to the slow onset nature of many climate risks.[lxx] Debate has also existed as to how best address climate-forced migration patterns. Data and insights from third-order satellite analyses can be instructive in both aspects. We have shown in the previous section that micro-mobility patterns among and between cities in neighboring countries are detectable and correlated with many key climate change variables. This is necessary to take into account for Warsaw Mechanism considerations of climate-forced migration as an aspect of loss and damage. In addition, funding mechanisms and risk transfer schemes should be time-variant, which means acknowledging the seasonality of many climate-related effects. These insights can be used in a pre-emptive manner when large shifting patterns like El Niño and La Niña are expected to occur. They can also be tailored to regions such as East Africa or other localities, which each face distinctive local challenges.

5.3 Conclusions

International climate policy is a critical arena that affects all aspects of sustainable development down to a local level. The top-down nature of international policy should not negate the experiences and pressing needs of the general population. Satellite remote sensing and data blending with other sources, as well as direct engagement with affected parties, will have an important role in the future directions of policies and actions alike. In order to achieve the greatest benefit of utilizing these technologies, proactive and extensive efforts must be made to see the unseen, both in terms of populations that are not visible or do not have large footprints and also in terms of insights and dynamic trends that may be difficult to detect at first glance but nevertheless have an indelible impact on the populations experiencing them.

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