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Volume 6 | Issue 1 | January 2023 | Page1-68
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Contents

Articles

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ARTICLE

Peri-urban Development: Discussion with Land Use Zoning, Statutory Provision, and Issues inside Katahari Rural Municipality, Nepal

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ABSTRACT

The peri-urban area is a transitional zone between the city and its hinterlands characterized by mixed land use and intensive flows of resources, people, goods, and services from and to the city center. These zones are generally misguided and haphazardly developed without a proper planning framework. The peri-urban area at present will be the urban area in the future; therefore, it needs planning intervention in its initial stage of growth. Katahari, a peri-urban area of Biratnagar metropolitan city, is developing a spontaneous lack of land use plans. Recently, the Government of Nepal has encouraged the local government to implement land use plans in the provided framework, policy, and guidelines. This study, in this context, attempts to analyze and identify land use issues and potential zones for Katahari rural municipality that also supports planning urban development in the future. The study is based on primary and secondary data and information supported by maps and figures. It is concluded that Katahari has been developed as a multi-function center adjoining the Biratnagar metropolitan city, and future expansion of the city will cover a wide range of rural municipalities. The postal highway that passes through it has attracted a wide range of urban functions. Agriculture, residential, commercial, and industrial are the main land use category at present and needs development control through providing land use zoning and related planning instruments through the increasing role of the stakeholder and the government agencies in the decision-making processes and implementation of spatial development frameworks to regulate peri-urban development in the area which will guide the future planning for liability, economic viability, social inclusion, and environmental sustainability in the area. Spill-over development activities of Biratnagar, have increased the number of economic activities, population growth, and mixed-use development.

Keywords: Peri-urban; Land use; Urban expansion; Spill-over development; Rural municipality; Agriculture

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1. Introduction

In Nepal, urbanization has generally been practiced analyzing terms of the number of municipalities and people living in them, and these municipalities are at the crux of the struggle to achieve better living standards [1] and are concentrated mainly in the valleys (Kathmandu, Pokhara), inner Tarai (Triyuga, Hetaunda, Chitwan, Dang-Deukhuri) and main highway corridor and in the towns nearer to the Indian border. These urban areas are becoming a center of attraction for the people and are expected to serve as hubs to provide markets for goods and services and improved living conditions and employment for the city dwellers as well as those in the surrounding rural localities [2]. Urban growth is inevitably linked to peri-urban areas [3] through the process of spatial expansion of the functions in the periphery [4] and there also exists a spillover effect of the nearby cities.

The conversion of rural space into urban is an important indicator of urban growth in Nepal. Rapid migration from rural to urban centers has demanded land for housing, industry, trade facilities, open space, waste disposal, etc. in the peripheral area of the urban centers. Moreover, the reclassification of rural into urban areas is one of the main driving forces of urban growth in Nepal [5]. These urban areas have focal or nodal characteristics [6], and people will have continued to leave rural areas and move to urban centers to escape adverse conditions [1]. However, urban area depends to a considerable extent on the outside area for their support [7]. The outside area of the urban center which is also called a ‘peri-urban’ or ‘urban fringe’ or ‘suburban’, is growing rapidly in many cities today.

Land use zoning is a tool to control the haphazard growth of a city. It promotes the city as more sequential, orderly, and planned. Land use zoning is the most common form of land-use regulation and is used by cities and municipalities to guide development. Many people have understood that the term ‘zoning’ and ‘planning’ same and have similar meanings. But these are different meanings having complementary natures. Urban planning is the way that people adapt the land to suit their needs whereas zoning is how the government regulates the land. It allows for a better site for planning, design, and development intervention in the large flank of urban space. Both emphasized land (space). Land use planning provides a framework for the spatial development of the urban area. A well-planned urban area is a well-prepared urban area, anticipating the future allows for better preparedness; and good land use planning positively impacts the development of the urban economy.

Many urban centers are growing without proper planning in Nepal. Although, huge planning documents were prepared in the past in the context of planning urban development. One of the major components of these plan documents was to manage urban areas through proper land use zoning. But these are poorly implemented. As a consequence, most of the urban centers are accreting desultorily. In this scenario of urban development, there is an urgent need to regulate urban areas through proper land use planning and zoning. Many urban centers including newly emerging municipalities do not have land use planning. Moreover, peri-urban areas are spontaneously developed around the relatively big urban area full of lack land use plans. Recently, the Government of Nepal has encouraged all rural municipalities, and municipalities to prepare land use plans in the framework by providing policy and guidelines. In this context, this study attempts to identify land use issues and potential zones in the context of Katahari rural municipality. This study focuses on the land use plan prepared based on the existing urban development trends and scenarios.

2. Review of literature

Understanding Peri-Urban Zone: In much urban literature, the peri-urban area has been defined in terms of a ‘transitional zone between the city and its hinterlands characterized by intensive flows of natural resources, goods, and services from and to the city [8-10], which has developed on the particular landscape and distinct but interconnected spatial units and open spaces with a wide range of functions [11], and characterized by changing local economic and employment structures from agriculture to manufacturing, rapid population growth, and migration, rising land values and mixed land use and weak institutional structure [8,9,12]. These features are coexisted and develop beyond the legal administrative boundaries and frequently evolve into a new form of dynamism that expands and shrinks geographically, moves to the peripheral area, and is swallowed by the core area [13]; a city, in this context, rely on the distributive role through providing services including the population of the peripheral areas/regions through sustainable transport networks: Systematic integration of migrants into the urban economy; regulating access to outside entrepreneurs and investments [14].

The peri-urban area can be differentiated from both urban and rural areas due to its rapid growth and dynamic and mixed physical, environmental and economic as well as social attributes [15]. In recent years, rapid urbanization and growing city are due to job opportunities, security, education, health, and commercial business centers that resulted in huge land and housing lack in cities are giving enormous pressure on peri-urban areas [12]. The boundary of peri-urban areas is porous and transitory [3], and the area of transition from rural to urban and land use change at the urban-rural edge in the peri-urban landscape requires the lens of spatial arrangement from both urban and rural perspectives to shape, manage and preserve the ecosystem that people depend upon [16].

Urban economic base [17], threshold and range of goods [18], and basic and non-basic components of urban function [19] are one or other ways discussed peri-urbanization processes, which support and from the relatively bigger city developed in the adjoining area. Peri-urbanization is not a new issue in the planning literature [8]; however, before industrialization, it had little meant. In the age of industrialization, the urban planner was aware of the potential emergence of a spatial form of urban expansion beyond the urban boundary. Ebenezer Howard (1898), a British urban planner, introduced the concept of 'garden city' by making clear boundaries between the city and countryside, and planning on a concentric pattern of development with open space, public parks, and radial boulevards [20]. Peri-urbanization created immense pressure on the local environment and becoming a challenge to control in recent years in Nepal due to rapid encroachment of agricultural land, unauthorized land fragmentation, and unveil infrastructure and development plans.

Peri-urban land use: City is more than buildings, streets, utilities, steel, concrete, and glass; nevertheless, these are the materials from which the physical structure is made [21]. In addition, the city is a symbol of civilization or historic-cultural and archeological marks, and a product of human nature [22]. Therefore, city planning urges to prepare and implement to improve the esthetic pattern of an urban environment. The initial step in the direction of modern planning can be traced to practices of establishing zoning-a legal permitted of the use of land. Indeed, zoning is a statistical exercise and a prognostication of the urban environment, and not only establishes the uses to which land may be put, but it sets the standards by which improvements upon the land may be developed. Most cities have classified their land into different macro and micro zones today. In a larger city, there may be many zones (class) whereas in a small town there may be few classes. These differences in class/zone of land use do not suggest (less) accuracy in determining the classification, rather they indicate that land used in a small town is less complex than in a large city [21].

Nepal's demographic transformation is characterized by fast-growing population density in Kathmandu valley, highway corridors, and close to the border with India [5]. Non-farm economic activities are concentrated in and around Kathmandu valley and towns developed close to the Indian border. Biratnagar and Birganj are such examples of clustering non-farm activities and play the role of a service center for the rural hinterland, where manufacturing largely takes place. Each larger city/town has its hinterland and range of goods and services beyond the administrative boundary, mostly covering the peri-urban zone at the periphery. In the recent development process, there exists a relationship between the city and its peripheral area in terms of the flow of goods, people, and services that creates immense pressure on the land resources; as a consequence, agricultural land has been converted into a built-up area. These changes, therefore, become a major challenge to the periphery [9]. The process of converting agricultural land into the built-up area in the peripheries of Nepal with rapid population growth, industrial development, and consequently, rapid spatial and temporal pattern of changes. Increasing numbers of brick kilns around the urban and peri-urban areas of Nepal have decreased agriculture production and productivity in recent years. Study shows that a brick kiln removes an average of 1500 MT of soil per 0.05 ha per year [23]. The removal of fertile topsoil causes a loss of nitrogen (N), phosphorus (P), and potassium (K) in soil [24], which is causing an alarming loss of prime agricultural land [25]. These kinds of changes invite a new way of thinking about the use of land and livelihood diversification [9]. This also makes it a question to retain fertile agricultural land and a farming system to supply food grains. Therefore, to retain fertile agricultural land together with the expanding economic opportunities in the peri-urban area; a new form of planning needs to be imposed, primarily that is land use zoning and ultimately guided planning norms and standards.

Land Use Act 2019, Land Use Policy 2015, and Land Use Regulations 2022 (Government of Nepal) are the major policy instruments to address unforeseen land use changes in the urban and rural areas of Nepal. Even though, poverty and poor landowners in the peri-urban areas have been selling their land due to social obligation to meet their daily needs. As result, land brokers (both organized in the name of the private real-estate developer or in-organized individuals and groups) are always pushing poor communities out of the city and urging them to go periphery. Therefore, peri-urban land is directly or indirectly controlled by them, and makes change the use of land according to their voice and choices which are not planned, surveyed, and without basic infrastructure services. Somewhere, land brokers are buying large plots of farmland and sub-dividing into several small parcels with poor infrastructures and selling parcels at a high price. A large number of small landholders residing in the periphery of the urban area generally sold their land to brokers and purchased it away from the city area [26].

Many private landowners and brokers are acting as a developer in Nepal even without holding a legal license and without planning permits [12]. This is true in the case of many municipalities and urbanized villages in Nepal. Biratnagar metropolitan city, for example, has proposed ring road covering Katahari, Lakhantari, Jhorahaat, Buddhanagar, Tankisinuwari, and Hattimuda of the periphery area are becoming a center of attraction among the land brokers, private developers, and common people. This process of land development has lost fertile agricultural land and created immense pressure on agriculture by developing residential and industrial/commercial units, especially after the 1990s [27].

2.1 Land use plan: The policy context

Land use planning is a tool to support the orderly occupation and use of land and to avoid adverse developments. It primarily relies on an evaluation of the land and on the alternative patterns of its use including the physical, social, and economic conditions which affect that use to choose the most applicable use [28]. FAO's Guidelines for Land Use Planning (1989, 1993) make it clear that in the long run, land use must be economically feasible and socially respectable, and that one major thing of development planning is to make effective and productive use of the land. Modern land use planning holds always an environmental component, and in this respect, it is often restrictive in the kind of land uses permitted. The basic principle in this respect is that good quality land should be preserved and any form of land degradation should be avoided [29,30]. It will also guide urban expansion, open space management, conservation of natural resources, and cultural resources, and sustainable development of (peri) urban area.

Most of the municipalities/rural municipalities in Nepal are lacking land use plans for line-up development and therefore are lacking land regulation and control development plans. Periodic plans and Integrated Urban Development Plans (IUDP) are sectoral plans mostly the rural municipalities and municipalities are practicing. However, the plan is also lacking proper implementation initiatives and therefore fails to address all level problems of the municipality [31]. Similarly, the periodic plan does not properly address the land use plan and haphazard growth and land use practices are taking place. In this context, a land use plan is crucial for land management in Nepal.

2.2 Land management and statutory provision of land use categories

Looking at the history of land management in Nepal, there was no statutory provision for land classification in Nepal. In the very beginning, the customary land tenure system prevalent in Nepal was Raikar, Birta, Jagir, Rakam, Guthi, and Kipat, declared by the rulers. It means the traditional form of land tenure in Nepal was state ownership, especially before the 1950s [32]. After 1964, a land registration system has been established. cadastral surveying and other legal instruments such as the Land Register (Moth), Restriction Register, Survey Field book, and Parcel Map came into existence. Accordingly, all lands in the country have been divided into different parcels, and each parcel has a unique identity. According to Land Revenue Act (1978), eight different land tenure systems have been noted: Government lands, public lands, Raikar lands (in the name of the owners), Guthi lands, Guthi Raitan Nambari in the name of the owner (Guthi lands converted to Raikar or Raitan Nambari), Land and building on possession in the name of the user, Birta Lands, and Haal Aabadi lands (virgin or unregistered lands) in the name of the tiller. The land classification has also been in terms of the cadastral map. These maps are on different scales such as 1:500, 1:1250, and 1:2500 depending on the land value, parcel size, and population density [32].

Land Act 1963, has graded land into four classes: Abbal, Doyam, Sim, and Chahar in the irrigated (Dhanahar/Khet land) and no-irrigated lands (Bari/Pakho land) of Tarai and hills region of Nepal. Until the promulgation of the National Land uses Policy 2012 and the establishment of the National Land Use Project (NLUP) in 2000, the grading system was dismissed.

The government of Nepal approved the National Land Use Policy 2069 [33] which was replaced by Land Use Policy 2072 (2015) after the earthquake disaster of 2015 and its impacts on the different parts of Nepal. Recently, the government of Nepal enacted the Land Use Act 2076 (2019) and Land Use Regulation 2022 which intended to manage land based on the Geology, carrying capacity and suitability of land, existing land use, and the nation's need [34]; accordingly, land has been categorized into 10 zones such as Agricultural, Residential, Commercial, Industrial, Mines and Minerals, Cultural and Archeological, River-stream-lake-wetland, Forest, Public Use and Open Space, and other zones (Nepal Gazette, August 13, 2019; and June 6, 2022, GoN). For the urban area, due to its sensitivity, micro-zoning provision has also been set up in the land use regulations 2022. It emphasized the safe and secure settlement along with environmental protection and ensuring food security. Furthermore, for the effective implementation of land use zones in the country, Land Use Regulations 2022 has directed for an institutional setup of the Federal Land Use Council at the national level, Provincial Land Use Council at the province level, Local Land Use Council at the local level, and Implementation Committee at Rural municipality and municipality level at the bottom.

3. Materials and methods

3.1 Study area: Katahari rural municipality

Katahari Rural Municipality lies on the right bank of the Lohandra river and the left bank of the Singiya River; adjoining Biratnagar Metropolitan City in eastern Nepal with a total area of 55.4065 sq km (**Figure 1**). The area falls within the Tarai physiographic region of Nepal and the northern rim of the Indo-Gangetic plain (IGP). The total population of the rural municipality was 48,625 in 2021 [35], and divided into seven wards. The annual population growth rate in the rural municipality between 2011-

2021 has been calculated at 2.3 percent.

3.2 Preliminary study and data collection

The methodology for this study comprises of analysis of collected primary and secondary data, as well as the incorporation of suggestions from major stakeholders and communities regarding the preparation of land use planning for Katahari rural municipality. The consultation meeting was organized at the local level in a series of steps and methods. Particularly, rural municipal-level and community-level meetings were organized to collect issues/information to fulfill the objectives of this study. To achieve the objectives of this study, the study adopted the following steps of the methodology and the flow chart of methodology steps shown in **Figure 2**.

Preliminary study and data collection

The first stage of the work includes the preliminary work before starting the field survey. This includes collecting and reviewing relevant documents, literature, maps, and photographs and preparing the datasheet for the records of physical, and socio-economic data as well as an inventory of existing infrastructures.

Supporting documents of the study

Secondary data (Reports, Books, Documents, Profile, Maps, etc.) were collected and natural resources such as rivers, rivulets, ponds, physical infrastructures, Land use (forests, agricultural lands, residential areas, barren land as well as plans and programs) was indicated in map of suitable scale. In addition, socio-economic information and land use studies of the rural municipality have been collected and reviewed. A checklist of information required during field investigation was prepared in the meantime, and formats/data sheets and procedures for the data collection were finalized before mobilization of the fieldwork. At least, the following documents,

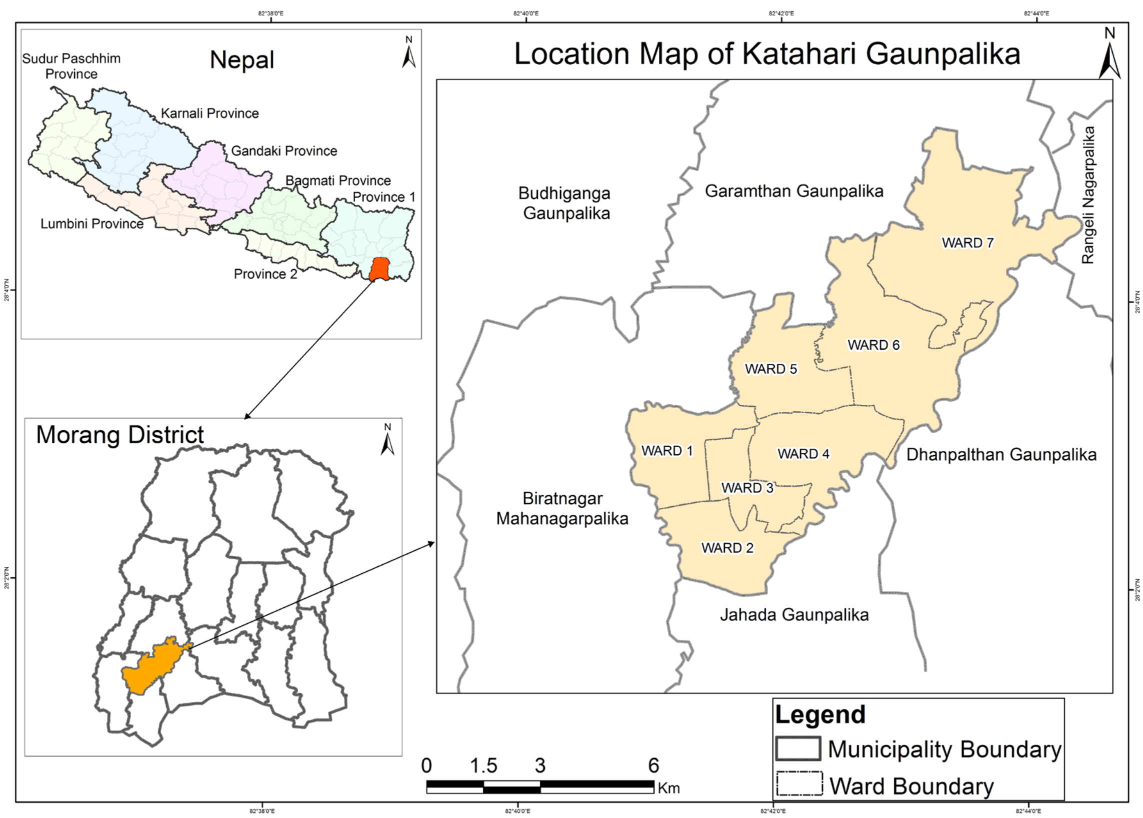

Figure 1. Location of Katahari rural municipality.

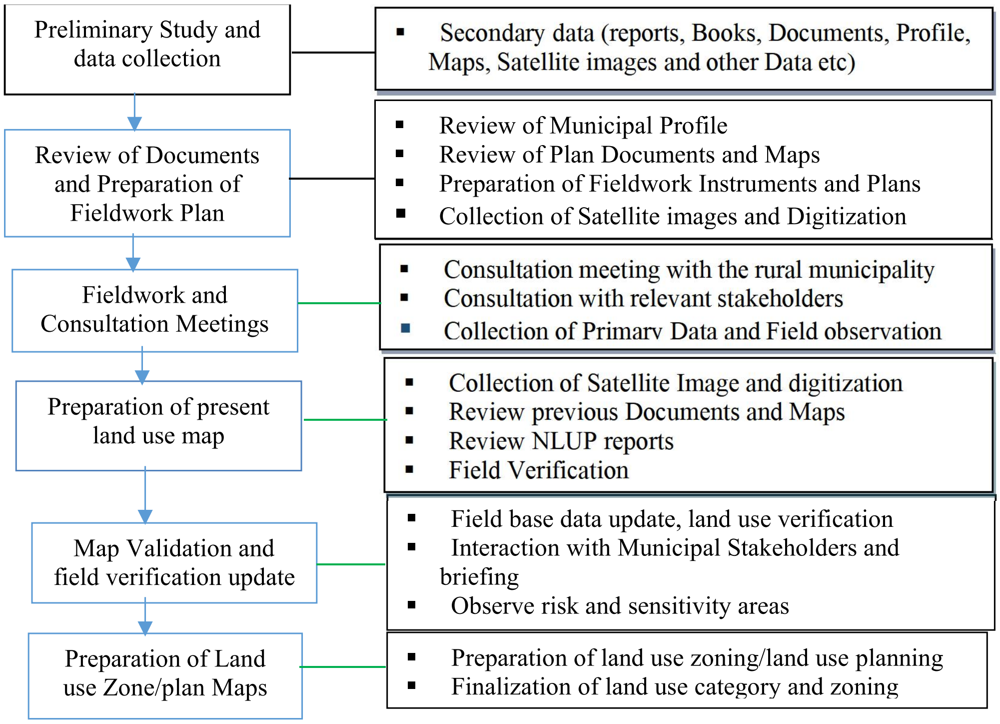

Figure 2. Simplified steps of methodology.

literature, maps, and photographs were collected and reviewed:

- Topographic maps prepared by survey department 1:25000 scale
- Katahari rural municipality maps (including ward division)
- Base map (updated) of Katahari rural municipality
- Integrated urban development plan, Katahari rural municipality 2018
- Integrated settlement concept paper, DUDBC, 2015
- Rural municipality profile
- Building bye-laws and regulation

Field observation and map update

The field inspection and study have been carried out. The inspection and study were done based on an existing development scenario, existing physical infrastructures, industrial areas, institutional areas, business areas, agriculture practices, urbanized areas, residential areas, and environmentally sensitive areas. In addition, the existing situation of the government, and non-governmental institutions within the rural municipality have been located in the maps. During the field investigation, existing land use practices were verified by using satellite images.

Discussion and interaction with stakeholders

An interaction meeting was conducted at Katahari rural municipality office. During the meeting, the approach and methods for the preparation of a land use plan, key indicators to be covered in the land use plan, the definition of the land use plan, etc. were discussed. Furthermore, in such an interaction meeting, presented the land use policies and issues with rural municipal authorities and local communities to identify the rural municipal level issues and problems relating to the land use planning. Similarly, local-level integration meetings at the ward level were held.

4. Results and discussion

4.1 The framework of land use plans inside Katahari rural municipality

Present land use and land use zones

Katahari is a rapidly growing market center with a high degree of functional range and magnitude. Agriculture, built-up, riverine, and lake reservoir are the dominant land use categories in Katahari. Agriculture practices are found slowly decreasing due to increasing human settlements and market centers on the main roads side; particularly in, Katahari and Nayatol areas. Conversion of agricultural land into residential use has also been observed along both sides of Hulaki Rajmarga (postal highway). Market side, Katahari, Nayaroad, Khairbana, Anantaram Chowk, Thalaha, and Bhaudaha are expanding rapidly. Traditional farming practice is common. In recent years, the conversion of agricultural land into residential, industrial, and commercial purpose around postal highway have also been noted significantly. There are altogether 49 industries in the rural municipality. They include poultry farms, sawmills, and brick factories. Among them, brick factories have brought significant changes in local land use patterns. Altogether 16 brick factories are noted and most of them are recorded in the middle and northern sides of the Rural Municipality (Bhaudaha and Thalaha area) (**Figure 3**).

Similarly, the postal highway of Katahari rural municipality section has established several medium scales processing industries and fuel centers; where agricultural land has been rapidly converted into industrial and commercial use. Similarly, migration has also been increasing in recent years in the rural municipality; and people, particularly from the northern hill districts and the vicinity areas, are attracted to settle around the rural municipality which is also brought a significant change in land use. Newly emerging markets, well-established road connectivity, proximity to Biratnagar metropolitan city

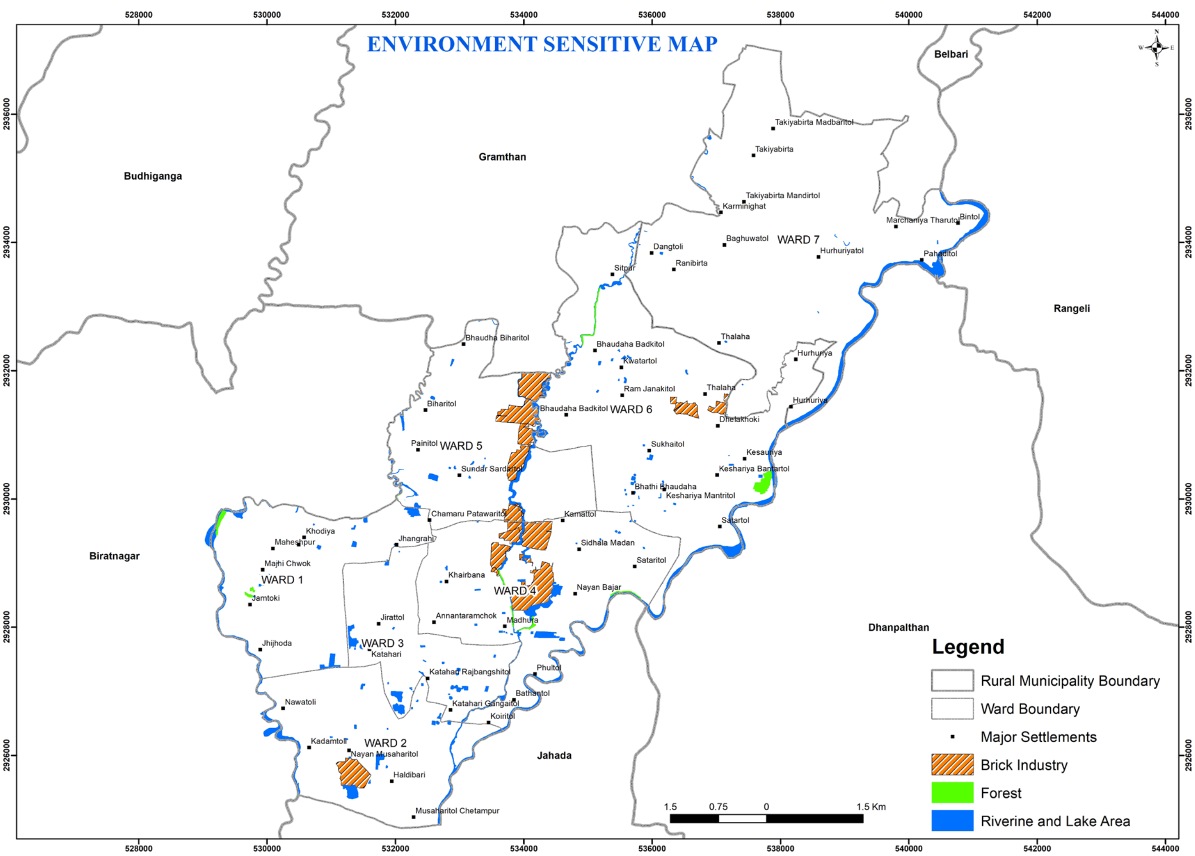

Figure 3. Location of brick factories in Katahari rural municipality.

and Indian markets, and developing infrastructure and institutions are key to attracting people, goods, and services to the rural municipality.

Thus, taking into consideration the above issues, land use zoning of the rural municipality has been proposed. Agricultural land is proposed for residential, industrial, commercial (mixed as well as commercial), and public use and open space as compensation for the major strategic and district road expansion and to meet the need for population growth. Land of marginal utilization with a low capability of agricultural production is allocated for the residential, commercial, and industrial areas as far as possible. In the exception case, only residential and commercial area was allocated to highly fertile arable land. Mainly, the residential area was allocated to the surrounding residential and infrastructure-developed area. As stated above few residential, commercial, agricultural, and industrial areas have been allocated for public use purposes i.e., roads and open spaces as per the rules of Right of Way. After reviewing the risk factor and land capability of the area, only less-productive lands with very low-risk factors and far from industrial areas and flood-prone areas are recommended for new residential areas. These new residential areas are not proposed in flood-prone areas, areas under industrial pollution, and other risks. Therefore, the residential and commercial areas are almost at minimum risk. The topography of the rural municipality is nearly flat and not susceptible to landslides.

The potential land use zone has allocated the maximum area for the agricultural zone (64.96%) followed by the residential zone (17.31%), industrial (5.63%), and commercial (3.12%). Regarding crops, cereal and cash crops are mostly produced in this area. Rice and wheat are the main cereal crops whereas pulses, oilseeds, and vegetables are the major cash crops grown in this area. Few people have shown their interest in fish farming and agro-forestry, especially along the riverside. Soils are mostly fertile so they are more suitable for agriculture [36]. The mines and mineral sites, Excavation areas, and undersigned other land use sites do not exist however, some river banks are being used to excavate sands and stones informally by the local people, which is not mentioned here due to the low volume of extraction. Compare with the present land use of the study area, the agricultural area is decreased by 931.51 hectares while zoning. The main reason behind this is the allocation of new sites for residential, commercial, and industrial uses. Around 577 ha of agricultural land has been additionally allocated for the new residential site and 163 ha for the new commercial site (**Table 1**). Similarly, a new industrial zone has also been proposed in the study area.

According to the National Population Census 2021 (preliminary result), the annual population

Table 1. Comparison of present land use and land use zoning.

SN	Types	Present Land Use		Land Use Zoning		Difference (Area in ha.)	Absolute Change (%)	Relative Change (%)
		Area (in ha.)	%	Area (in ha.)	%			
1	Agriculture	4530.73	81.77	3599.22	64.96	–931.51	–16.81	–20.56
2	Forest	15.94	0.29	80.36	1.45	+64.42	+1.16	+404.14
3	Residential	381.44	6.88	910.09	16.43	+528.65	+9.55	+138.59
	Land Development	0.00	0.00	48.82	0.88	+48.82	+100.00	0.00
4	Commercial	9.73	0.18	172.79	3.12	+163.06	+2.94	+1675.85
5	Riverine and Lake	284.66	5.14	312.08	5.63	+27.42	+0.49	+9.63
6	Public Use & Open Space	98.58	1.78	104.10	1.88	+5.52	+0.10	+5.60
7	Industrial	218.42	3.94	312.04	5.63	+93.62	+1.69	+42.86
8	Cultural and Arch	1.15	0.02	1.15	0.02	0.00	0.00	0.00
9	Total	5540.65	100.00	5540.65	100.00	0.00		

growth rate of Katahari Rural municipality is 2.3% in between 2011-2021; and it is expected that the population of the Rural municipality in the next 15 (2036) years would be 68,396. It has also been observed that the urbanization rate seems high in recent years, and there also exists a spillover effect in Biratnagar metropolitan city. Internal migration from hills and other areas, proposed railway station, proposed dry port, proximity to Biratnagar, access to India (Jogbani/Forbesganj), close to regional airport Biratnagar, high access to health and education facilities, fertile agriculture land have collectively attracted to the people living in the Katahari rural municipality area. Importantly, due to its locational advantages, many people are choosing this area for better residential and industrial activities. Increasing investment in remittance on residential plots and increasing social trends of the single-family system are also reasons for migration into Katahari. Therefore, significant growth can be seen in residential zoning. Buildings in this area are used for mixed purposes i.e., residential and commercial purposes. Some new commercial and business areas are also proposed considering the future demand of the increasing size of the population in this area. As the Katahari lies in the eastern corner of Biratnagar, many industrialists have chosen this area to establish their industrial and business activities due to its cheap land, labour, and local tax. Most of the forest area and cultural and archeological areas are kept intact while zoning in the rural municipality.

Anecdotal evidence, interaction with the local community, and field verification/observation reveal that some areas of the rural municipality suffered from flood and inundation related to rainfall. Lohandra and Singiya rivers are devastating in nature during the rainy season. Their impacts seem huge along both edges of the river channel. Therefore, these areas are proposed agroforestry in some areas and/or kept in riverine and lake zone for other zoning purposes.

In the present zoning, areas under the agriculture zone are dominant followed by a residential area, industrial, riverine and lake, public use, and open space area. The industrial area is also remarkable growth in the rural municipality. The cultural and archeological areas are not on a significant scale. Mines and mineral sites, excavation areas, and undersigned other land use sites do not exist. The decrease in agricultural area is due to the allocation of new sites and areas for residential, industrial, commercial, and public use and open space use. Most of the agricultural land in the rural municipality has the land capability of class I which has been used for agricultural purposes [37].

To allocate agricultural land for new residential, commercial and industrial, land capability data were reviewed which was prepared by NLUP 2072c [38]. Land of marginal utilization with a low capability of agricultural production is allocated for residential, commercial, and public use and open space areas as far as possible. In the exception case, only residential and commercial area was allocated to highly fertile arable land. Mainly, the residential area was allocated to the surrounding residential and infrastructure-developed area.

Similarly, the commercial area is allocated at the main core business area in the existing residential extent, and high possibility of industrial activities along the postal highway, commercial activities at the trading nodes/Bazar areas, other major road junctions, and high development of available commercial infrastructure. The final output of the zoning framework is presented in **Figure 4**.

4.2 Rural shrinking vs urban spill over development

Katahari Rural municipality is located eastern part of Biratnagar Metropolitan City. East-west *Hulaki Rajmarga* (postal highway) has also crossed the Rural municipality. But the Rural municipality had a better experience of the shrinkage of trade and business after the construction of the East-West highway in the past decades, due to shifted trading activities towards the east-west highway nearby towns and markets. Some business communities and local people also migrated to Biratnagar and other urban centers for a better livelihood. However, *Hulaki Rajmarga* (postal highway), a national priority project

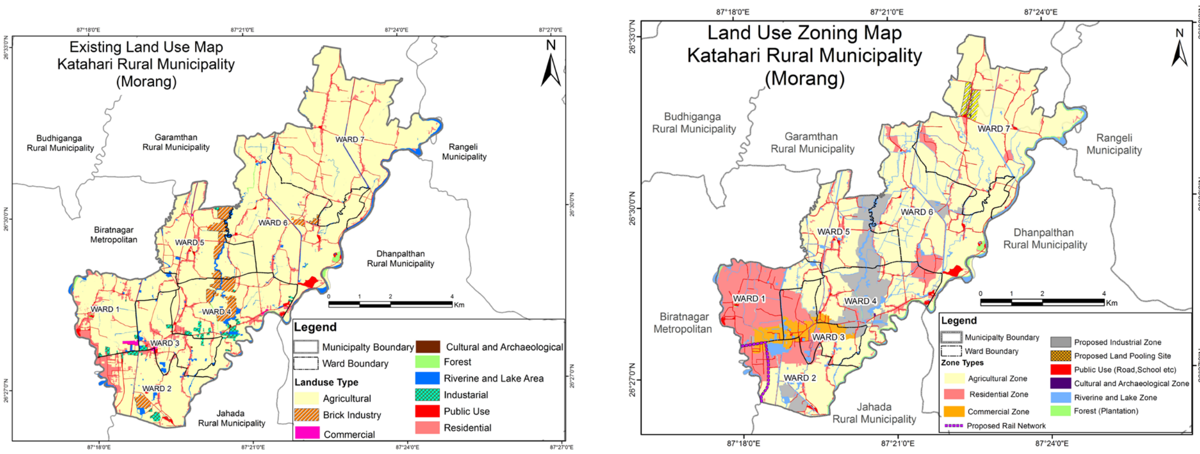

Figure 4. Comparison between present land use and land use zoning in Katahari rural municipality.

is under construction; and it is expected that after the completion of the project, it would enhance the further development of the rural municipality and attract the local business communities and people living in the vicinity areas of the district and region. One of the main attractions is the construction of a postal highway, which is connected Rangeli-Gauriganj-Bhadrapur to the east and Biratnagar to the west. Importantly, Rangali and Gauriganj are selected new towns to be developed in the Tarai region of Nepal [39]. Therefore, most of the fertile agricultural fields are rapidly converting into residential, industrial, and commercial zones. The infrastructural facilities such as roads, education, health, electricity, and telecommunication need to be developed to match the current rate of development, which remains a major future concern for urban development and its consequences on land use change in the rural municipality. Katahari is also proposing a site dry port and a railway station in the area. Therefore it is also expected that infrastructure and facilities need to be developed further. After the implementation of land use zoning, Katahari will have experience with planning urban development. As a consequence, the future development scenario of Katahari will depend on:

- Continued construction and eventual completion of the Integrated Checkpoint south of Katahari.
- Construction and upgrading of new strategic and urban /village roads that connects the railway station, and postal highway.
- Proposed Biratnagar ring road covering Katahari.
- Construction and completion of a new rail link from India to a new terminus located in Katahari.
- Construction and completion of Integrated Agriculture Development at ward no 1 of Katahari.
- Increasing the demand for residential parcels and construction of physical infrastructure.

Afterward, Katahari will be experienced with:

- Accelerated population growth, with increasing in migration.
- Increase the demand for residential parcels and the potential of expanding residential areas.
- Potential to overcome mixed use of land.
- Establish an industrial zone at the east of Biratnagar, expansion of industrial activities; potential to increase new jobs and employment mostly for low-income workers.
- A rapid expansion improved brick factories and poultry farms.
- Encouraging agglomeration economies through the promotion of polycentric settlements and functions.
- The potential industrial centre of the east of Biratnagar. The industrial zone to the east will create another center and will be connected by road (Postal highway) and railway (Katahari Junction proposed) and Integrated Checkpoint (Budhanagar, south of Biratnagar).

Katahari Developing as a Peri-Urban zone of Biratnagar Metropolitan City: Biratnagar is located in the eastern Tarai region, close to the border with India, designated municipal status in 1914) and upgraded into metropolitan city status in 2017 (2074 BS). It is an industrial, trading, and administrative center of Nepal; and a provincial capital and had a 2,44,750 population in 2021 [36] making it the sixth most populous metropolitan city in the country after Kathmandu, Lalitpur, Bharatpur, Pokhara, and Birgunj; plays a leading role in the economy of the country. The trade treaty of 1923 between Nepal and British India contributed to the gradual emergence of urban centers in Tarai that helped to achieve some level of industrial development in localized spaces in Tarai from the 1930s which have now become a full-blown city like Biratnagar [2]. The study reveals that there were drastic changes in the temporal and spatial dynamics of land use/land cover afterward. Urban and industrial areas are very much enlarged and cultivated and forest areas considerably decreased during the study periods 1978-2009 [41]. It is a metropolitan city anchored on a core city surrounded by suburban areas whose economies are becoming highly integrated with Biratnagar. Katahari (to the east), Tankisinuwari, Hattimudha, Duhabi (to the north) Buddhanagar to the south are developing as a peri-urban center of Biratnagar. These areas are undergoing profound demographic, economic, cultural, and environmental changes creating considerable challenges and stress for their residents and the ecosystems upon which they depend for their livelihood and quality of life [16].

4.3 Land use issues in Katahari rural municipality

Main land use issues in the study area have been pointed out below:

- Increasing resource consumption in the process of urban development due to the declining viability of agriculture raises the issue of whether agricultural land should still be preserved or not.
- Low-density urban sprawl, mainly through scattered construction of private residences.
- Low-intensity use of many plots in the market area and a city center, i.e. inefficient use of prime land with high commercial potential.

Other issues that address the land use in Katahari are given below:

- Weak implementation: Problems are related to the effectiveness of the implementation process. There is a lack of seriousness in enforcing land use control. Land use classes are vague with a lack of clarity on what is permitted and what is not. Public control measures are not often explicitly laid out.
- The wider scope and significance of land use planning and the need for land use control have yet to be articulated and ingrained in the planning documents.
- Katahari does not yet have a comprehensive regulatory framework that would meet its specific needs in controlling land use. As a result, major challenges remain unsolved regarding how to manage haphazard growth.
- Lack of political will: The planning framework is not adequately legitimized or accepted or implemented, if the political will practice properly in a strategic place.
- There is a lack of qualified and motivated development planners to steer the planning process. It is necessary to train them to enable them to deal with the emerging challenges of urban development.
- Conflict of interest between the elites and relatively rich influential persons.
- In this scenario, the vision of Katahari will not be achieved properly. The vision has been articulated in the Integrated Urban Development Programme (IUDP) prepared by the Rural municipality in 2018 [42].

One of the major objectives of the land use policy enacted in the country is to retain fertile agricultural land. Sustainable Development Goal (SDG-2) has also emphasized food security and sustainable agriculture, which can be possible only through the preparation and implementation of a proper land use plan. There are several plans and policies prepared in the past for the local government to support sustainable agriculture and other infrastructure development. But these are mostly failures due to their poor performances. Katahari rural municipality (the local government) should prepare their land use plans by addressing the above issues including planned (urban) development which will help to select the land where development should take place. The local government has also encouraged commercial farming and paid attention to promoting medium and small-scale industrial enterprise development in the relatively less productive marginal lands. This study helps local governments to make their land use policy and plan environmentally sustainable, economically vibrant, and socially inclusive.

5. Conclusions

Land use planning is a multidisciplinary exercise. It regulates land resource according to meet people's needs, and discourage sporadic and unwanted development activities on the land resource. The government of Nepal has enacted a land use act and land use policy; and attention has been made to preparing land resource maps (e.g., present land use, soil, land capability, risk layer, land use zoning, cadastral layer superimposed and profile) of the respective rural municipality and municipalities. Although, land use and planning are highly influenced by elites and politicians in society. A lack of long-sighted planning is still prevalent in the area. Whatever prepared pans in the past were not matched spatially in the real ground. Therefore, there is a need for spatial planning for addressing effective implementation. Land use Act 2076 provides ample scope for land use planning through broader categories of the land but these classifications are not yet practiced. Sometimes this created a confused among the farmers, landlords, and developers. This makes challenges for the proper implementation.

Katahari has been developed as a multi-function center with a wide range of functions that intensities of land use change. Biratnagar-Rangeli postal highway passes through this rural municipality, where mostly mixed land use (agriculture, residential, commercial, and industrial) has been developed. Land use patterns in Katahari have emerged sporadically and are not uniform or structured. To reduce this problem, land use zoning and planning instruments need to be intervened through the increasing role of the stakeholder and the government agencies in the decision-making processes and implementation of spatial development frameworks to regulate peri-urban development in Katahari. Land use zones, therefore, have been prepared that guide the future use of land, and the placement of necessary infrastructure. Land uses zones are not mutually exclusive and they are not isolated from each other. In the case of Katahari, spill-over development activities of Biratnagar, have increased the number of economic activities, population growth, and mixed-use development, as a peri-urban area of Biratnagar metropolitan city, is somehow unified spatial features, and it has a fuzzy phenomenon evolving between urban and rural characteristics. After analysis of the situation, it has been suggested that Katahari can be classified into three types of development:

- First: Those areas, that have been socio-economic incorporated into the main city e.g. Biratnagar, as classified as predominantly urban areas.
- Second, potential urban areas experiencing early land conversion and residential development.
- Third, some of the peri-urban areas are dominated by manufacturing and other large land-consuming industrial activities.

Three zones namely: Agriculture, residential and industrial are prominent in Katahari rural municipality that will guide the future planning for liability, economic viability, social inclusion, and environmental sustainability of the area.

Main land use issues in the study area have been pointed out below:

- Increasing resource consumption in the process of urban development due to the declining viability of agriculture raises the issue of whether agricultural land should still be preserved or not.

- The wider scope and significance of land use planning and the need for land use control have yet to be articulated and ingrained in the planning documents.
- The planning framework is not adequately legitimized or accepted or implemented if the political will practice properly in a strategic place.
- There is a lack of qualified and motivated development planners to steer the planning process. It is necessary to train them to enable them to deal with the emerging challenges of urban development.
- Conflict of interest between the elites and relatively rich influential persons.
- Some of the peri-urban areas are dominated by manufacturing and other large land-consuming industrial activities.

Conflict of Interest

There is no conflict of interest.

References

[1] Sharma, R.P., 2012. Urbanization, planning and development: Consequences, opportunities and future [Internet]. SAMBRIDHI, a Development Journal of Center of Development Studies [Accessed 2020 August 25]. Available from: https://www.academia.edu/2029224/Urbanization_Planning_and_Development_Consequences_Opportunities_and_Future.

[2] Devkota, K., 2018. Challenges of inclusive urbanization in the face of political transition in Nepal. Joshua, Mugambwa Mesharch, W., Katusiimeh (editors). Handbook of Research on Urban Governance and Management in the Developing World. USA: IGI Global. Available from: http://www.Sias-southasia.org.

[3] Maheshwari, B., Singh, V.P., Thoradeniya, B., 2016. Balanced urban development: Is it a myth or reality? Basant, M., Vijaya, P., Singh Bhadranie, T. (editors), Balanced Urban Development: Options and Strategies for Liveable Cities. Springer Open: New York. Available from: https://link.springer.com/content/pdf/10.1007%2F978-3-319-28112-4.pdf.

[4] Kleemann, J., Inkoom, J.N., Thiel, M., et al., 2017. Peri-urban land use pattern and its relation to land use planning in Ghana, West Africa. Landscape and Urban Planning(Elsevier). 165, 280-294. Available from: www.elsevier.com/locate/landurbplan.

[5] Muzzini, E., Aparicio, G., 2013. Urban growth and spatial transition in Nepal: An initial assessment. Washington DC: The World Bank. 1. Available from: https://openknowledge.worldbank.org/handle/10986/13110.

[6] Shrestha, C.B., Manandhar, M.S., 1994. Settlement systems, small towns and market centers in the Bagmati zone sub-region. ICIMOD: Kathmandu.

[7] Shrestha, C.B., Rijal, S.P., 2015. Revisit to functional classification of towns in Nepal. The Geographical Journal of Nepal. 10, 15-27.

[8] Hudalah, D., 2010. Peri-urban planning in Indonesia: Contexts, approaches, and institutional capacity [PhD thesis]. Groningen, Netherlands: University of Groningen. Available from: http://www.rug.nl/research/portal/files/33030177/03_c3.pdf.

[9] Varkey, A.M., Manasi, S., 2019. A review of peri-urban definition, land use changes and challenges to development. Urban India. 39(1). Available from: http://www.researchgate.net/publication/335910837_A-Review_of_Peri-Urban_DefinitionsLand_Use-Changes_and_Challenges_to_Development.

[10] Vejre, H., 2009. Land use, land cover and soil sciences—Volume 4: Soils and soil sciences. 1. Encyclopedia of Life Support Systems (EOLSS): Oxford. Available from: https://www.eolss.net/sample-chapters/c19/E1-05-04-08.pdf.

[11] Wandl, A., Magoni, M., 2017. Sustainable planning of peri-urban area: Introduction to the special issue. Planning Practice and Research. 32(1), 1-3. doi: 10.1080/02697459.2017.1264191.

[12] Thapa, S., 2015. Booming land development in peri-urban Kathmandu; who should capture the incremental land value to provide water supply to Citizen? Final ICHUD Research Proposal Report. International Course on Housing and Urban Development: Rotterdam. Available from: http://researchgate.net/profile/Saraswati_Thapa/publication......pdf.

[13] Miljkovic, J., Zivanovic, C.T., Maric, I., 2012. Land use planning for sustainable development of peri-urban zone. SPATIUM International Review. (28), 15-22.

[14] MoUD, 2016. Third United Nations conference on housing and sustainable urban development (Habitat III)-Nepal national report. GoN, Ministry of Urban Development: Kathmandu. Available from: http://habitat3.org/wp-content/uploads/Nepal-HII-National-Report_email.pdf.

[15] Simon, D., McGregor, D., Nsiah-Gyabaah, K., 2004. The changing urban-rural interface of African cities: Definitional issues and an application to Kumasi, Ghana. Environment and Urbanization. 16, 235-245.

[16] Thorbeck, D., Troughton, J., 2016. Connecting urban and rural features through rural design. Basant, M., Vijaya, P., Singh Bhadranie, T. (editors), Balanced Urban Development: Options and Strategies for Liveable Cities. Springer Open: New York. Available from: https://link.springer.com/content/pdf/10.1007%2F978-3-319-28112-4.pdf.

[17] Alexander, I.N., 1954. The basic and non-basic concept of urban functional analysis. Economic Geography. (30), 246-261.

[18] Alber, R., Adams, J.S., Gould, P., 1971. Spatial organization: The geographers view of the world. New Jersey: Prentice-Hall.

[19] Mayer, H.M., Kulan, C.F., 1959. The economic base of cities. Mayer, H. M., Kulan, C.F.(editors), Readings in Urban Geography. Chicago: Chicago University Press.

[20] Garden city movement [Internet]. Wikipedia. Available from: https://en.wikipedia.org/wiki/Garden_city_movement.

[21] Gallion, A.B., 1950. The urban pattern, city planning, and design. USA: D.Van Nostrand Company, ING.

[22] Park, R.E., 1952. Human communities, the city and human ecology. The Free Press: Illinois, USA.

[23] Thapa, S., 2011. Brick Kilns: A threat to urban agriculture in Kathmandu, Nepal [Internet]. City Farmer News. Available from: http://www.cityfarmer.info/2011/08/22/brick-kilns-a-threat-tokathmandu.

[24] Tuladhar, B., Raut, A.K., 2002. Final report on environment and health impacts of Kathmandu's brick kilns. Clean Energy Nepal: Kathmandu.

[25] UNDP, 2016. Urban growth trends and multi-hazards in Kathmandu valley. United Nation Development Programme (UNDP)/Comprehensive Disaster Risk Management Programme: Kathmandu.

[26] Rao, P.S., Singh, H., Purohit, R.C., 2016. Changing economic scenarios of the peri-urban area of udaipur city, India. Basant, M., Vijaya, P., Singh Bhadranie, T.(editors), Balanced Urban Development: Options and Strategies for Liveable Cities. Springer Open: New York. Available from: https://link.springer.com/content/pdf/10.1007%2F978-3-319-28112-4.pdf.

[27] Upreti, B.R., Breu, T., Ghale, Y., 2017. New challenges in land use in Nepal: Reflections on the booming real-estate sector in Chitwan and Kathmandu valley. Scottish Geographical Journal.133(1). doi: 10.1080/14702541.2017.1279680.

[28] Verheye, W.H., 2009. Land use planning: Land use land value and soil sciences—Volume 3. Encyclopedia of Life Support System (EOLSS): Oxford.

[29] FAO, 1993. Guidelines for land-use planning. Food and Agriculture Organization of The United Nations: Rome. Available from: http://www.fao.org/3/t0715e/t0715e00.htm.

[30] FAO, 1995. Planning for sustainable use of land resources towards a new approach. FAO Land and Water Development Division: Rome, Italy.

Available from: http://www.fao.org/3/V8047E/V8047E00.htm.

[31] Dahal, K., Timalsina, K., 2017. New towns development: A wave of the future planning practices in Nepal. Tribhuvan University Journal. 31(1-2). doi: 10.3126/tuj.v31i1-2.25346.

[32] Acharya, B.R., 2008. Land tenure and land registration in Nepal. Integrating Generations FIG Working Week 2008; 2008 Jun 14-19; Stockholm, Sweden. Available from: http://www.fig.net/resources/proceedings/fig_proceedings/fig2008/papers/ts07b/ts07b_02_acharya_2747.pdf.

[33] Ministry of Land Reform and Management (MoLRM), 2012. National Land Use Policy 2012. MoLRM: Kathmandu.

[34] Ministry of Land Reform and Management (MoLRM), 2022. Land Use Regulations 2022, MoLRM: Kathmandu.

[35] CBS, 2021. National population census 2078, preliminary result. Central Bureau of Statistics: Kathmandu.

[36] NLUP 2072, 2015. Preparation of soil map of Katahari VDC.

[37] NLUP 2072, 2015. Preparation of Land Capability of Katahari VDC.

[38] NLUP 2072, 2015. Preparation of Land Use Zoning of Katahari VDC.

[39] DUDBC 2074, 2017. Feasibility study of new towns in the tarai-madhesh area of Nepal, Kathmandu.

[40] Rimal, B., 2012. Spatiotemporal dynamics of land use pattern response to urbanization in Biratnagar Sub Metropolitan City, Nepal. Engineering Science and Technology: An Internal Journal. 2(75-85). Available from: https://www.researchgate.net/publication/281759032_Spatiotemporal_dynamics_of_land_use_pattern_response_to_urbanization_in_Biratnagar_Sub-Metropolitan_City_Nepal.

[41] IUDP, 2018. Preparation of Integrated Urban Development Plan (IUDP) of Katahari rural municipality. Katahari Rural Municipality: Morang.

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ARTICLE

Assessment of the Impacts of Thunderstorm on Flight Operations at Murtala Mohammed International Airport, Ikeja, Lagos State, Nigeria

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ABSTRACT

The inefficiency of the aviation industry and the persistent rise in aviation hazards have been linked to weather phenomena. As a result, researchers are looking for better solutions to the problem. The study examined the impact of thunderstorms on flight operations at Murtala Mohammed International Airport, Lagos. The data on thunderstorms and flight operations were sourced from Nigerian Meteorological Agency (NiMet) and Nigerian Airspace Management Agency (NAMA) respectively. In order to meet the research target, descriptive statistics (mean, standard deviation, and charts) and inferential statistics (Pearson's Product Moment Correlation (PPMC) and Regression) were used. The significance level for all inferential analyses was set at 5% (0.05). The study revealed that 77.4% of thunderstorms occurred during the rainy season (April-October) while 22.6% occurred during the dry season (November-March). It also revealed some fluctuating movements of a thunderstorm in the study area. According to the findings, thunderstorms occur most frequently at the airport in June and less frequently in January and December. The study also discovered that thunderstorms at the airport are positively and significantly related to flight delays and cancellations, while the association between flight diversions and thunderstorm occurrence is positive but statistically insignificant. Furthermore, flight delays, flight diversions, and flight cancellations interact positively among themselves. The regression result of the study revealed that a 1% increase in thunderstorm occurrence leads to a 19.4% increase in flight delay, a 7.1% increase in flight cancellation, and a 4.3% increase in flight diversion. As a result, the study presented various regression models that may be utilized to make predictions. The study proposes consistent thunderstorm observation at the airport and steady forecasts using the regression models, based on the findings. However, it further recommends that pilots, air traffic controllers, and meteorologists be trained and retrained so that they can provide better and more efficient services.

Keywords: Thunderstorms; Assessment; Impacts; Flight operations; Airport

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1. Introduction

The aviation transportation industry, more than any other mode of transportation is greatly affected by weather from thunderstorms, snow storms, strong winds (squalls, wind shear), fog, thick-dust haze as well as temperature and pressure extremes; therefore, every phase of flight has the potential to be influenced by weather [1-3]. The growth of the aviation industry in Nigeria and the increased adoption of air transportation as one of the best means of transport have been obstructed by various weather hazards [4]. Thus, there is a greater need for aviation weather forecasters to deliver quality forecasts.

Thunderstorms are big, vertically extended convective clouds that frequently have their apexes near the tropopause and their bases near the top of the boundary layer [5]. Thunderstorms are ferocious, short-lived meteorological disturbances that nearly always feature lightning, thunder, dense clouds, significant amounts of rain or hail, and strong gusts of wind [6]. Layers of warm, moist air rise in a strong updraft to cooler areas of the atmosphere, whereupon thunderstorms form [6,7]. At that location, the updraft's moisture condenses to create imposing cumulonimbus clouds and, eventually, precipitation [6]. Cooled air columns then descend toward the ground, producing powerful downdrafts and horizontal winds [6,7].

In addition, electrical charges build on ice and water droplets that make up cloud particles [6,8]. When the electric charge that been collected is sufficiently high, lightning discharges happen [9]. When lightning strikes, it instantly and intensely warms the surrounding air, creating shock waves that sound like thunderclaps [6,10]. Occasionally, air vortices that are spinning and powerful enough to create tornadoes are present with intense thunderstorms [6].

Nearly all parts of the planet are known to have thunderstorms, though they are uncommon in the Polar Regions and seldom in latitudes higher than 50° N and 50° S [6,11]. However, thunderstorms are most common in tropical and temperate regions of the earth [6]. The characteristics of thunderstorms themselves are used to categorize or classify them, and these characteristics are heavily influenced by the meteorological environment in which the storms develop [5]. There are various types of thunderstorms.

When moisture is available at low and intermediate levels of the atmosphere—that is, from close to the ground's surface up to about 10,000 meters in altitude—and when there are mild winds that do not fluctuate significantly with height, isolated thunderstorms are more likely to develop [5]. These storms are sometimes known as local thunderstorms or air masses [12]. They often do not cause violent weather near the ground, are largely vertical in structure, and have a limited lifespan [6,12].

Storms with organized multiple cells, squall lines, or supercells are typically what cause violent weather on the ground, and they are known as multiple-cell thunderstorms [13,14]. Thunderstorms can occasionally form over a region with a diameter of hundreds of kilometers as a result of the formation of a mesoscale meteorological disturbance [13]. These disturbances include frontal wave cyclones, which are low-pressure systems formed by waves on fronts separating warm and cool air masses, and low-pressure troughs at higher altitudes [6]. Mesoscale convective systems (MCS) are the name for the storm pattern that results from this [6]. MCSs are usually connected with powerful multiple-cell and supercell thunderstorms [5]. Rainfall from stratiform clouds (cloud layers with a large horizontal extent) and convective clouds are frequently produced by these systems [6].

When environmental winds are favourable, a storm's updraft and downdraft organize, twist around, and reinforce each other [5]. As a result, a long-lived supercell storm forms [5,13]. These thunderstorms are the most powerful kind [5,6,13]. An anvil-shaped updraft rises, turns counterclockwise, and exits to the east [15]. Supercells have a two-to-six hour lifespan [6,16]. They are the storms that are most likely to cause noticeable wind and hail damage as well as strong tornadoes [17].

A thunderstorm is a very significant climatic element that affects all forms of transportation, such as roads, water and air. The effects of thunderstorms on flight operations at Port-Harcourt International Airport were assessed [18] utilizing simple and multiple bar charts and Pearson's product-moment correlation. Due to the meridional movement of the weather/ITD zones, the study found that thunderstorms usually occur during the rainy season months (monsoon periods), with an increasing trend over time. In addition, the study found that thunderstorms were responsible for 32% of flight cancellations (218 occurrences), 0.2% of diversions (291 occurrences), and 24% of delays (526 occurrences) at the airport between 2008 and 2013. The study also revealed that, with correlation values of r = 0.57, 0.49, and –0.04, thunderstorms have a greater effect on the number of flight cancellations and delays than on flight diversions respectively. The study came to the conclusion that thunderstorms occur during monsoon seasons in the study area and have a greater impact on delays and cancellations than on diversions.

The impact of thunderstorms on landing traffic at Frankfurt Airport (Germany) was studied [19]. The study, which considered all days, found that a thunderstorm moving over the Frankfurt airport area affects about 100 inbound aircraft within four hours of impact time with a total delay of about 1,000 minutes, or about 800 minutes longer than the typical delay for this time period. According to the report, Frankfurt Airport is significantly impacted by thunderstorms.

These studies have undoubtedly contributed to a better understanding of thunderstorm events, making it easier to detect and make predictions at Murtala Mohammed International Airport. The objectives of the study are; to determine the temporal variation of a thunderstorm at Murtala Mohammed International Airport and to determine the relationship between thunderstorms and flight delays, diversions and cancellations at Murtala Mohammed International Airport.

To the researchers' knowledge, there are few, if any, published studies that looked at the relationship between thunderstorms and flight delays, cancellations and diversions at Murtala Mohammed International Airport. As a result, this study's findings can provide some references and valuable information for similar scholars looking to better understand the impacts of a thunderstorm on flight operations.

2. Materials and methods

2.1 Study area

Murtala Mohammed International Airport, Lagos State is the study area. The major contributor to air traffic delays at Murtala Mohammed International Airport in Lagos is weather [20]. Four major weather conditions account for the occurrence of low visibility at Murtala Mohammed International Airport, and they are haze, rain, fog and mist [21]. **Figure 1** is the satellite image of Murtala Mohammed International Airport.

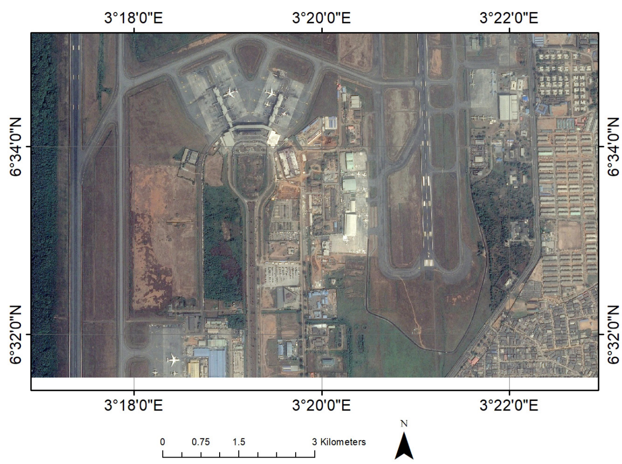

Figure 1. Satellite Image of Murtala Mohammed International Airport.

Source: Onwuadiochi et al., 2021.

Murtala Mohammed International Airport, Lagos has a tropical wet and dry climate [22]. The West African monsoon system (driven by the migration of the inter-tropical discontinuity) as well as mesoscale processes drive the rainy season, which lasts from March to November (with peaks in July and September) [23]. In August, there is a brief dry spell, followed by a prolonged dry season from December to March [24]. Murtala Mohammed International Airport (MMIA) is an international airport in Ikeja, Lagos State.

2.2 Data collection

The time-space for the thunderstorm data is from

2001 to 2020, as this research intends to examine the impact of weather, in this case, thunderstorms on flight operations. The time-space for the flight operations data is from 2008 to 2020, as this is the period of data that the researcher could access. The study basically relies on secondary data. The monthly thunderstorm data were obtained from the records of the Nigerian Meteorological Agency (NiMet). The thunderstorm detector was designated at Murtala Mohammed International Airport, Lagos State to detect thunderstorms in the terminal area. The Meteosat of Second Generation (MSG) and Real Time Imagery (RETIM) were used to monitor the development and decay of storms at the airport. The monthly data on flight delays, diversions and cancellations were obtained from the records of the Nigerian Airspace Management Agency (NAMA) at Murtala Mohammed International Airport, Lagos State.

2.3 Data analysis

The statistical analytic techniques that were employed to achieve the research target, which is the impact of a thunderstorm on flight operations (flight delays, cancellations and diversions) include descriptive statistics (such as mean, standard deviations, and charts) and inferential statistics including Pearson's Product Moment Correlation (PPMC) and Regression. All inferential analyses were judged at a 5% (0.05) level of significance.

2.3.1 Descriptive statistics

Descriptive statistical techniques were employed to describe the behaviour of the thunderstorms, flight delays, diversions and cancellations data series over the period of study. Particularly, the mean and standard deviation captured the centre and spread of the dataset, while the charts pictured the seasonal and annual trends of the data series. The temporal variation of a thunderstorm at Murtala Mohammed International Airport was ascertained by computing the descriptive statistics and also estimating the seasonal differences whereby April-October is the rainy season while the dry season period is November-March.

2.3.2 Pearson's correlation

Pearson's correlation analytic technique was employed in validating the extent and relationship among the study variables without suppressing the other. This statistical technique was considered appropriate as the data series of the variables under investigation were all converted to continuous data through log transformation. Geometrically, Pearson's correlation coefficient is generally computed as:

$$r = \frac{Cov\,(M,N)}{\sqrt{(Var\,(M))(Var\,(N))}} = \frac{\sum_{i=1}^{T}[(M-\bar{M})(N-\bar{N})]}{\sqrt{\left[\sum_{i=1}^{T}(M-\bar{M})^2\right]\left[\sum_{i=1}^{T}(N-\bar{N})^2\right]}} \quad (1)$$ [25]

where,

r is the correlation coefficient,

$Cov\,(M,N) = \sum_{i=1}^{T}[(M-\bar{M})(N-\bar{N})]$ is the covariance of M and N series,

$Var\,(M) = \sum_{i=1}^{T}(M-\bar{M})^2$ is the variance of M series,

$Var\,(N) = \sum_{i=1}^{T}(N-\bar{N})^2$ is the variance of N series.

T = Total number of observations,

$\bar{M}$ and $\bar{N}$ and mean values of series of M and N values,

M and N are variables of interest.

2.3.3 Regression analysis

The functional relationships among the selected variables were determined using the classical linear regression analytic technique. Geometrically, the relationship is represented as:

Number of Flight diversions, delays and cancellations = f(thunderstorm)

Such that:

LFDS, LFDL, LFCL = f(TSM) (2) [25]

where,

FDS = Number of flight diversions

FDL = Number of flight delays

FCL = Number of flight cancellations

L = Log-transformational operator

TSM = Thunderstorm

Analytical packages that were used include Microsoft Excel, Eviews and Statistical Package for Social Sciences (SPSS) version 25.0 for windows.

3. Results and discussion

The thunderstorm data for the year 2001 to 2020 are presented in **Table 1**. The time span for the data is because this study intends to examine the impact of weather, in this case the thunderstorms on flight operations.

As shown in **Table 1**, within the period under study, the highest thunderstorm event occurred in June with a value of 327. This is followed by September, October and July with values of 288, 262 and 254 respectively. The lowest thunderstorm event occurred in January with a value of 29. This is followed by December and February with values of 40 and 60 respectively. However, **Table 1** shows that the highest thunderstorm events occur during the rainy season while there is a decrease in thunderstorm events during the dry season. In addition, considering the cumulative thunderstorm, the highest number of thunderstorm events were experienced in the year 2019 with a cumulative value of 121. This is followed by the years 2014 (115), 2017 (114) and 2012 (110).

The data for the monthly totals of flight delays, diversions and cancellations for the year 2008 to 2020 are presented in **Table 2**.

As shown in **Table 2**, the highest number of flight delays was observed in October with a value of 83. This is followed by May and June with the values 79 and 73 respectively. The lowest number of flight delays was observed in December with a value of 18, and followed by January with a value of 21. Similarly, the highest number of flight cancellations was observed in September with a value of 41, followed by October and May with values of 40 and 39 respectively. The lowest number of flight cancellations was observed in January with a value of 15. This is followed by December and February with the values 18 and 22 respectively. Furthermore, the highest number of flight diversions was observed in July with a value of 51. This is followed by June and August with the values 47 and 40 respectively. The lowest number of flight diversions was observed in October with a value of 21, and followed by February and December with a value of 24.

Table 1. Thunderstorm Data (2001-2020).

Months													
Years	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Total
2001	0	2	3	4	7	16	9	13	14	10	4	1	83
2002	1	1	2	9	8	20	11	6	19	11	7	1	96
2003	1	4	3	8	13	17	17	7	10	15	8	4	107
2004	3	3	7	9	16	10	6	9	17	15	5	1	101
2005	0	5	8	5	15	17	11	3	10	12	7	2	95
2006	3	4	5	5	14	16	13	11	19	12	6	1	109
2007	0	0	4	6	12	16	14	12	12	10	5	3	94
2008	1	0	7	7	17	20	19	11	13	11	1	2	109
2009	1	3	6	9	12	16	9	1	11	14	3	0	85
2010	0	0	1	9	14	12	18	17	20	16	1	0	108
2011	0	3	2	7	9	21	11	6	14	14	10	0	97
2012	1	5	8	8	11	19	14	5	12	13	11	3	110
2013	5	2	6	11	16	11	17	2	14	9	12	3	108
2014	6	5	7	8	10	18	17	11	13	9	9	2	115
2015	1	5	9	8	8	16	5	12	12	17	3	1	97
2016	0	0	6	5	10	13	10	9	15	15	3	1	87
2017	1	6	7	6	14	20	18	8	13	15	2	4	114
2018	0	5	2	6	14	16	13	13	17	13	5	1	105
2019	4	6	4	7	13	17	13	7	18	22	7	3	121
2020	1	1	6	8	8	16	9	1	15	9	7	7	88
Total	29	60	103	145	241	327	254	164	288	262	116	40	

Source: NiMet, 2021.

Table 2. Monthly totals of flight delays, diversions and cancellations data (2008-2020).

Months	No of flight delays	No of flight cancellations	No of flight diversions
January	21	15	32
February	31	22	24
March	62	35	33
April	61	34	31
May	79	39	37
June	73	32	47
July	65	36	51
August	39	27	40
September	69	41	30
October	83	40	21
November	32	23	31
December	18	18	24

Source: NAMA, 2021.

3.1 Temporal variation of thunderstorm at Murtala Mohammed International Airport

The trends of thunderstorms at Murtala Mohammed International Airport were determined both annually and monthly. The results are as presented in **Figures 2** and **3**.

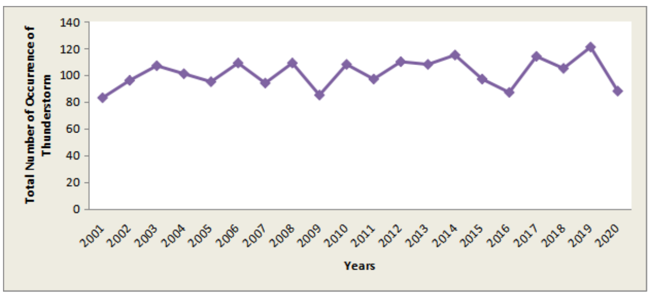

Figure 2. Annual trend measures of thunderstorm at Murtala Mohammed International Airport, Lagos.

The annual trend result of the thunderstorm as presented in **Figure 2** shows that between the years 2001 and 2003, there was an upward movement in the occurrence of the thunderstorm, that is 83, 96 and 107 respectively. However, there was a decline in the year 2004 down to 2005 with respective values of 101 and 95. Similarly, from the year 2006 through the year 2020, there has been an up and down movement in the annual occurrence of a thunderstorm at Murtala Mohammed International Airport. It shows an abrupt downward movement after having the highest cumulative thunderstorm events in 2019 with a value of 121.

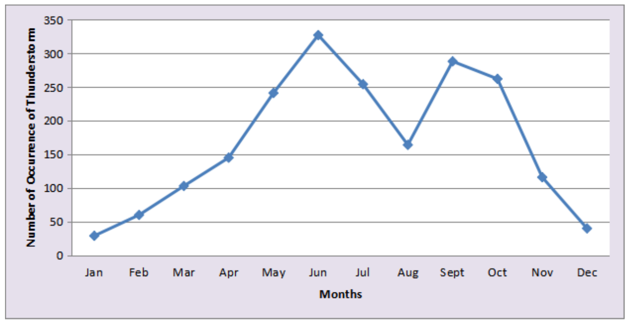

Figure 3. Monthly trend measures of thunderstorm at Murtala Mohammed International Airport, Lagos, from 2001 through 2020.

The monthly statistics of the occurrence of a thunderstorm at Murtala Mohammed International Airport, Lagos, covering the period from 2001 to 2020 as shown in **Figure 3**, indicates that from January through June, the number of occurrence of a thunderstorm at the airport are usually on a steady rise. The corresponding values are 29, 60, 103, 145, 241 and 327. However, in July (254) and August (164), it usually drops and rises again in September (288). From October, through to December, the frequency of occurrence of a thunderstorm at the airport drops substantially. The corresponding values are 262, 116 and 40. However, a thunderstorm is most experienced at the airport in June and less experienced in January and December during the year.

The descriptive statistics as presented in **Table 3** describe the monthly behaviour of the data series of the study variables. The result shows that from the year 2008-2020, an average of 52.75 ± 23.14 flights have been delayed at Murtala Mohammed International Airport, Lagos; an average of 30.17 ± 8.91 flights have been cancelled, while an average of 33.42 ± 9.08 number of flights have been diverted. However, the minimum number of flight delays that have been experienced for the period was 18 while the maximum was 83. The minimum number of cancelled flights was 15 while the maximum was 41. Also, the minimum number of the diverted flight was 21 while the maximum was 51. The series of flight delays and cancellations are skewed to the left (negatively skewed) while that of flight diversions is skewed to the right (positively skewed). Meanwhile, there was no excess kurtosis in the series of FDL, FCL and FDS for the period of study.

Consequently, the monthly average frequency of occurrence of a thunderstorm at the Murtala Mohammed International Airport, Lagos, from 2001 through 2020, ranges from 29 to 327. The mean stood at 169.08 with a standard deviation of 102.72, an indication of high volatile nature. The skewness estimate is positive (Sk = 0.76) while the kurtosis statistic is –1.476. Hence, the series is positively skewed and without excess kurtosis.

The seasonal statistics as presented in **Figure 4** shows that the number of occurrence of a thunderstorm during the rainy season is more than twice that of the dry season. Specifically, out of the total occurrence of a thunderstorm during the period, about 77.4% occurred during the rainy season while 22.6% occurred during the dry season.

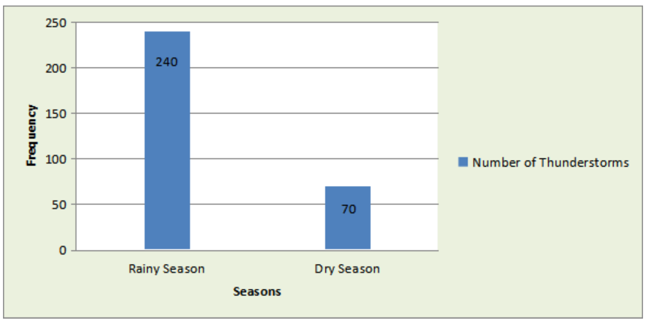

Figure 4. Seasonal variation of occurrence of thunderstorm at Murtala Mohammed International Airport, Lagos (*Rainy Season: April-October; Dry Season: November-March*) from 2001 to 2020.

3.2 Relationship between thunderstorm and flight delays, diversions and cancellations

The relationship between the occurrence of thunderstorms and flight delays, diversions and cancellations was estimated using Pearson's correlation statistics. The correlation matrix is presented in **Table 4**.

From the correlation result, flight delays and flight cancellations are positively and significantly associated with thunderstorms at the airport ($r > 0.50$, $p < 0.05$). Meanwhile, the relationship between flight diversions and the occurrence of a thunderstorm is positive but statistically insignificant ($r = 0.483$, $p = 0.1115 > 0.05$). Also, as presented in the correlation matrix result, flight delays, flight diversions and flight cancellations go in the same direction, such that they interact positively among themselves. Specifically, flight delays substantially increase the chances of flight cancellations ($r = 0.954$, $p = 0.0000$), while delays in flight infinitesimally (or insignificantly) increase the chances of flight diversions ($r = 0.223$, $p = 0.4868$) at the Murtala Mohammed International Airport, Lagos.

3.3 Regression estimates of the linkages between thunderstorms, flight delays, diversions and cancellations at Murtala Mohammed International Airport, Lagos

The regression estimates showing the level of influence of thunderstorms on a flight delay, flight diversion, and flight cancellation at Murtala Mohammed International Airport, Lagos, are presented in **Tables 5 through 7** below.

Table 3. Descriptive statistics of the research variables.

Variables	N	Min	Max	Mean	Std. Dev.	Skewness	Kurtosis
FDL	12	18.00	83.00	52.7500	23.14038	–0.301	–1.558
FCL	12	15.00	41.00	30.1667	8.91203	–0.454	–1.207
FDS	12	21.00	51.00	33.4167	9.08003	0.673	–0.061
TSM	12	29.00	327.00	169.0833	102.72245	0.076	–1.476

Source: Researchers' SPSS 25.0 computation, 2022

Note: FDS = Flight diversions; FDL = Flight delays; FCL = Flight cancellations; TSM = Thunderstorm.

Table 4. Correlation between occurrence of thunderstorm and flight delays, diversions and cancellations.

Correlation t-Statistic Probability Observations	FDS	FDL	FCL	TSM
FDS	1.000000 ----- ----- 12			
FDL	0.288262 0.951973 0.3636 12	1.000000 ----- ----- 12		
FCL	0.222625 0.722125 0.4868 12	0.954153** 10.08048 0.0000 12	1.000000 ----- ----- 12	
TSM	0.483197 1.745271 0.1115 12	0.861892** 5.374859 0.0003 12	0.813579** 4.424696 0.0013 12	1.000000 ----- ----- 12

Source: Researchers' computation 2022 using Eviews 10.

** Correlation is significant at the 0.01 level (2-tailed); FDS = Flight diversions; FDL = Flight delays; FCL = Flight cancellations; TSM = Thunderstorm.

Table 5. Regression estimate for FDL and TSM.

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	19.921	7.066	2.819	0.018
TSM	0.194	0.036	5.375	0.000
R^2 = 74.3%				
DW stat. = 1.420				

Source: Researchers' Extract from SPSS 25.0 Result, 2022.

From the estimated regression relationship in **Table 5**, the regression line is:

$$FDL = 19.921 + 0.194TSM$$

The regression result shows that thunderstorms with a coefficient value of 0.194, a t-statistic value of 5.375 > 2 and an associated probability value of 0.000 < 0.05 exert a significant positive influence on flight delays at Murtala Mohammed International Airport, Lagos. Specifically, a 1% increase in the number of occurrences of a thunderstorm would lead to about 19.4% increases in flight delays at the airport.

The goodness of fit of the model as estimated by R-Squared (R2 = 74.3%) indicates that the explanatory power of the model is high, thereby confirming that the linear model is a good one for estimating the relationship between the occurrence of thunderstorms and flight delays at Murtala Mohammed International Airport, Lagos, for the period of study. In the same vein, the Durbin-Watson statistics which takes care of the residual statistics uncovered that the model is free from first-order autocorrelation problems. This is because, DW stat. = 1.420 is closer to 2 than to zero.

Table 6. Regression estimate for FDS and TSM.

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	26.195	4.787	5.472	0.000
TSM	0.043	0.024	1.745	0.112
R^2 = 23.3%				
DW stat. = 1.254				

Source: Researchers' Extract from SPSS 25.0 Result, 2022.

From the estimated regression relationship in **Table 6**, the regression line is:

$$FDS = 26.195 + 0.043TSM$$

As shown in the regression line, a thunderstorm with a coefficient value of 0.043, a t-statistic value of 1.745 < 2 and an associated probability value of 0.112 > 0.05 has an insignificant positive influence on flight diversions at Murtala Mohammed International Airport, Lagos. From the coefficient result, a 1% increase in the number of occurrences of a thunderstorm would lead to about a 4.3% increase in flight diversions at the airport.

The R-Squared (R2) estimate shows that flight diversion did not have a good linear relationship with a thunderstorm. In other words, a thunderstorm is not a direct factor causing the diversion of flights at Mohammed International Airport, Lagos, as only about 23.3% of the total variations in flight diversions at the airport can be explained by a thunderstorm. The rest 76.7% are attributable to other factors not present in the model. More so, the Durbin-Watson statistic value of 1.254 is closer to 2 than to zero, an indication that the model is free from first-order autocorrelation problem.

Table 7. Regression estimate for FCL and TSM.

Variable	Coefficient	Std. Error	t-Statistic	Prob.
C	18.232	3.120	5.843	0.000
TSM	0.071	0.016	4.425	0.001
R^2 = 66.2%				
DW stat. = 1.612				

Source: Researchers' Extract from E-views 10 Result, 2022.

From the estimated regression relationship in **Table 7**, the regression line is:

$$FCL = 18.232 + 0.071TSM$$

The regression result as presented in **Table 7** shows that thunderstorms with a coefficient value of 0.071, a t-statistic value of 4.425 > 2 and an associated probability value of 0.001 < 0.05 exert a significant positive influence on flight cancellations at Murtala Mohammed International Airport, Lagos. From the result, a 1% increase in the number of occurrences of a thunderstorm would lead to about a 7.1% increase in flight cancellations at the airport.

In the content of the regression result, the goodness of fit (R-Squared) estimate of 66.2% indicates that about 66.2% of the total variations in flight cancellations at Murtala Mohammed International Airport, Lagos, can be explained by a thunderstorm. The model, therefore, is not a bad one for estimating the relationship between the occurrence of thunderstorms and flight cancellations at Murtala Mohammed International Airport, Lagos, for the period of study. The Durbin-Watson estimate of 1.612 is closer to 2 than to zero, and therefore confirmed that the model is not affected by the serial correlation problem.

4. Conclusions and recommendation

For the annual trend, the study shows that between the years 2001 and 2003, there was an upward movement in the occurrence of a thunderstorm, while it declined in the year 2004 down to 2005. However, from the year 2006 through the year 2020, there was an up-and-down movement in the annual occurrence of a thunderstorm at Murtala Mohammed International Airport.

The monthly statistics of the occurrence of thunderstorms indicate that from January through June, the number of occurrences of a thunderstorm at the airport increases. However, in the month of July and August, it drops and rises again in September. From October through December, the frequency of occurrence of a thunderstorm at the airport drops greatly. The study however shows that thunderstorm is most experienced at the airport in June and less experienced in January and December during the year.

The result reveals that from the year 2008 to 2020, Murtala Mohammed International Airport in Lagos experienced an average of 52.75 ± 23.14 flights that were delayed; an average of 30.17 ± 8.91 number of flights were cancelled; and an average of 33.42 ± 9.08 number of flights were diverted. However, the study developed regression models that could be used for predicting flight diversions, delays and cancellations at the airport. Based on the findings, the study recommends consistent thunderstorm observation at the airport and steady forecasts using the regression models. Furthermore, more research on thunderstorms is also needed, particularly in Nigeria and other tropical nations that experience thunderstorms more than elsewhere on the globe.

Conflict of Interest

There is no conflict of interest.

References

[1] Hosea, M.K., 2019. Effect of climate change on airline flights operations at Nnamdi Azikiwe International Airport, Abuja, Nigeria. Science World Journal. 14(2), 33-41.

[2] Onwuadiochi, I.C., Ijioma, M.A., Ezenwaji. E.E., et al., 2020. Effects of wind shear on flight operations in Sam Mbakwe Airport, Imo State, Nigeria. Tropical Built Environment Journal. 7(1).

[3] Onwuadiochi, I.C., Ijioma, M.A., Mage, J.O., et al., 2021. Comparative analysis of the measured and extrapolated wind shear distributions at Murtala Mohammed and Port Harcourt Interna-

tional Airports, Nigeria. Journal of Environment and Earth Science. 11(5), 63-78.

[4] Weli, V.E., Ifediba, U.E., 2014. Poor weather and flight operations: Implications for air transport hazard management in Nigeria. Ethiopian Journal of Environmental Studies and Management. 7(3), 235-243.

[5] Stull, R. (editor), 2017. Practical Meteorology: An algebra-based survey of atmospheric science. Sundog Publishing, LLC: USA.

[6] Krider, E.P., 2022. Thunderstorm. Encyclopedia Britannica [Internet] [cited 2022 Sep 4]. Available from: https://www.britannica.com/science/thunderstorm.

[7] UCAR, 2022. Center for Science Education [Internet]. Available from: https://scied.ucar.edu/.

[8] National Weather Service, 2022. Understanding lightning: Thunderstorm electrification [Internet] [cited 2022 Sep 5]. Available from: https://www.weather.gov/safety/lightning-science-electrification.

[9] Mazur, V., Ruhnke, L.H., 1998. Model of electric charges in thunderstorms and associated lightning. Journal of Geophysical Research. 103(D18), 299-308.

[10] Mohamood, N. (editor.), 2021. Struck by lightning. A Golden Meteorite Press: Canada.

[11] Seneviratne, S.I., Nicholls, N., Easterling, D., et al., 2012. Changes in climate extremes and their impacts on the natural physical environment. Field, C.B., Barros, V., Stocker, T.F., et al. (editors). Managing the risks of extreme events and disasters to advance climate change adaptation. A special report of working groups I and II of the intergovernmental panel on climate change (IPCC). Cambridge University Press: Cambridge, UK, and New York, NY, USA. pp. 109-230.

[12] Bureau of Meteorology, 2012. Hazardous Weather Phenomena: Thunderstorms [Internet] [cited 2022 Sep 6]. Available from: http://www.bom.gov.au/aviation/data/education/thunderstorms.pdf.

[13] Doswell III, C.A., 2015. Mesoscale Meteorology: Severe Storms [Internet]. Encyclopedia of Atmospheric Sciences (Second Edition) [cited 2022 Sep 6]. Available from: https://www.sciencedirect.com/topics/earth-and-planetary-sciences/thunderstorm.

[14] Rafferty, J.P. (editor), 2011. Dynamic earth: storms, violent winds and earth's atmosphere. Britannica Educational Publishing: New York.

[15] Brown, R.A., 2005. Thunderstorms. Oliver, J. E. (editor), Encyclopedia of world climatology. Encyclopedia of Earth Sciences Series. Springer: Dordrecht. pp. 719-724. doi: 10.1007/1-4020-3266-8_207.

[16] Bunkers, M.J., Johnson, J.S., Czepyha, L.J., et al., 2006. An observational examination of long-lived supercells. Part II: Environmental conditions and forecasting. Weather and Forecasting. 21(5).

[17] Wurman, J., Kosiba, K., White, T., et al., 2021. Supercell tornadoes are much stronger and wider than damage-based ratings indicate. PNAS. 118(14).

[18] Enete, I.C., Ajator, U., Nwoko, K.C., 2015. Impacts of thunderstorm on flight operations in Port-Harcourt international airport, Omagwa, Rivers State, Nigeria. International Journal of Weather, Climate Change and Conservation Research. 1(1), 1-10.

[19] Hauf, I., Sasse, M. (editors), 2022. The impact of thunderstorms on landing traffic at Frankfurt airport (Germany)—A case study. 10th Conference on Aviation, Range, and Aerospace Meteorology; 2022 May 14; Hannover, Germany. Germany: Institute of Meteorology and Climatology.

[20] Ayantoyinbo, B.B., 2015. Causative factors of air traffic delay in Murtala Mohammed International Airport Lagos, Nigeria. British Journal of Economics, Management & Trade. 8(3), 230-235.

[21] Ojoye, S., Yahaya, T.I., Iornongo, T., et al., 2019. Forcasting low horinzontal visibility in Murtala Mohammed Airport, Ikeja, Lagos,

Nigeria. International Conference on Climate Change Challenges and Prospects (NMetS 2019), Nigerian Meteorological Society.

[22] Fasona, M., Muyiolu, K., Soneye, A., et al., 2019. Temporal analysis of the present and future climate of the Lagos coastal environment. Unilag Journal of Medicine, Science and Technology (UJMST). 7(1), 113-128.

[23] Omotosho, J.B., Abiodun, J., 2007. A numerical study of moisture build-up and rainfall over West Africa. Meteorological Applications. 14, 209-225.

[24] Oteri, A.U., Ayeni, R.A., 2016. The Lagos Megacity: Water, Megacities and Global Change [Internet]. UNESCO/ARCEAU. Available from: https://www.researchgate.net/profile/Akomeno-Oteri/publication/313376479_Water_Megacities_and_Global_Change_Portraits_of_15_Emblematic_Cities_of_the_World/links/60436ab3a6fdcc9c781692b4/Water-Megacities-and-Global-Change-Portraits-of-15-Emblematic-Cities-of-the-World.pdf.

[25] Onwuadiochi, I.C., Ijioma, M.A., Ozoemene, M.L., et al., 2021. Mathematical modeling of the relationship between wind shear and aircraft operations at Murtala Mohammed and Port Harcourt International Airports, Nigeria. IOSR Journal of Mathematics. 17(3), 20-34.

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ARTICLE

Using the GPS Station to Study Wind and Coastal Morpho-dynamics in North-eastern Morocco

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ABSTRACT

The purpose of this work is to evaluate the potential of Global Positioning System (GPS) measurements for the monitoring of aeolian and coastal dynamics. The studied sites are the Moulouya estuary, Bouarfa's area and Tigri Chott. The study shows that GPS is used to determine the dune kinematics and the Moulouya estuary in 3-D with an annual temporal resolution and a sub-centimeter accuracy. The GPS measurements carried out between 2013 and 2021 have shown spatial and temporal variations of the dune kinematics and Moulouya estuary. The results presented here show that the GPS measurements have the capability of continuously surveying the geomorphological entities' kinematics with small and slow displacements and thus, they could complement conventional topometric techniques in a warning system.

Keywords: GPS; Monitoring; Coast; Dune; Northeast of Morocco

1. Introduction

Positioning techniques at different time and space scales have made progress in the last decades, particularly in the field of surveying and mapping or in the production of Digital Elevation Model (DEM), by digital photogrammetry [1,2], radar interferometry [3-5], DORIS system [6], or by Global Positioning System [7,8]. Although these methods are now commonly adopted for mapping, little attention has been paid, until now, to the potential use of GPS, for monitoring, occasional or continuous unstable natural sites or works of art [9].

In this context, the GPS technique has a role to play. This tool has many applications in various fields: Military and space, industry, meteorology,

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geography and geology, vehicle location, agriculture, cartography, etc. [10-12].

Today, GPS has become a common and widely used geomatics technique [13-15]. The use of GPS data makes it possible to determine the relative positions of points located up to several hundred kilometres away, with an accuracy of a few millimeters.

In order to evaluate the capacity of the GPS technique, a study was carried out in order to determine the coastal and wind dynamics in some sites of eastern Morocco. It has, in fact, shown the direction of displacement of the coastline and the dunes of the region of Bouarfa and Chott Tigri. The results obtained make it possible to evaluate the advantages and disadvantages of GPS for continuous monitoring in order to consider a device adapted to real-time.

This work makes it possible to georeference, using GPS, the data provided by the two GPS stations, and therefore to produce thematic maps. A similar study was done in the same area, but it only covered 3 years: 2013-2015 [16,17]. This paper presents, in a more detailed way, the coastal dynamics of the mouth of Moulouya, the dunes of Bouarfa and Chott Tigri, over the period of 2013-2021.

2. Presentation of the study area

2.1 Situation

A study was carried out in eastern Morocco in three different sites: The mouth of Moulouya in the north, Bouarfa and Chott Tigri in the south (**Figure 1**).

2.2 Presentation of relief and geology

The mouth of the Moulouya is experiencing significant dynamics. It was measured by multi-date photo-interpretations [18,19]. The rate of erosion was estimated at 8m/year from 1958 to 1988. The displacements of the shoreline are currently monitored using a network of markers. The continuous measurements of these movements purported to determine the coastal dynamics and validate the models of propagation of this type of dynamic.

The Bouarfa region is located in the eastern High Atlas, made up of narrow parallel mountain ranges, in an E-W direction, framing high plains (**Figure 2**). The ranges have low altitudes (1400-2100 m). The plains of Tamlelt and El Biazza have altitudes

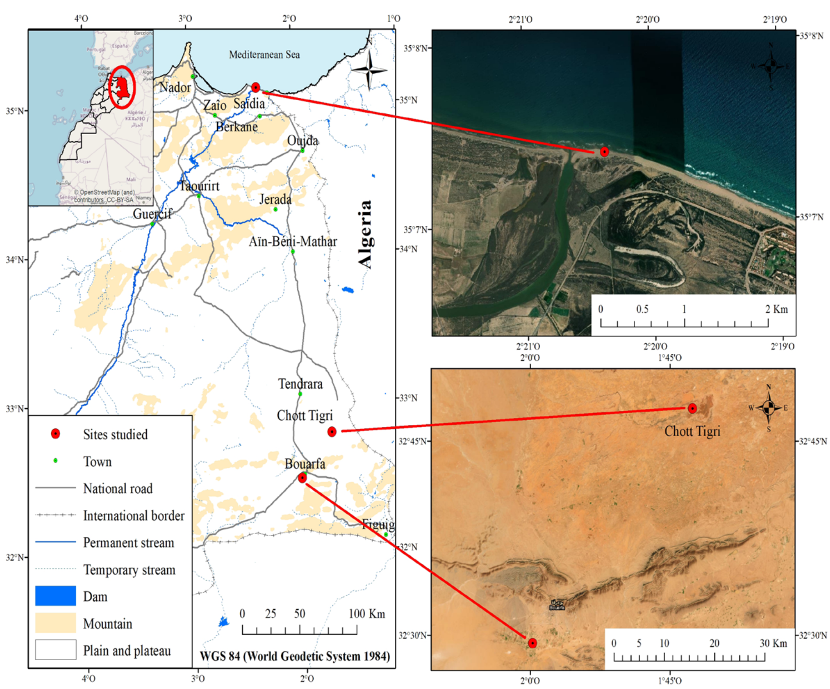


Figure 1. Studied area and location of measurement sites.

ranging from 1100 m to 1200 m. They are depressed compared to the Hauts Plateaux which border them to the north. These are large basin-shaped plains bordered on all sides by the Jurassic and Cretaceous formations of the Atlas. They have, in their center, a discontinuous backbone formed of Paleozoic sediments [20].

Figure 2. Sand beds on the northern slopes of the mountain ranges south of Maâder El Msarine (south of Bouarfa).

The Chott Tigri extends from the High Plateaux of eastern Morocco 60 km northeast of Bouarfa around 1300-1400 m altitude (plateau) and 1100-1200 (basin). It stretches 60 km from west to east and 30 km from north to south. It looks like an irregular ellipse, bounded to the north and south by almost straight cliffs (**Figure 3**). This closed basin is traversed by a little evolved hydrographic network (O.Mazer, O.Meril) meandering in the middle of recent dune formations, draining the waters towards the sebkha which occupies the center (Ed-Dechar). The series of red sandstones of Chott is Senonian. The visible thickness of these layers is estimated at 500 m [21] (**Figure 4**).

Figure 3. General view of the Chott Tigri.

Figure 4. Detail landscapes in the Chott Tigri.

It results from the destruction of the vault of an anticline by the erosion processes imposed by the climate: Torrential gullies following rare and violent rains, deflation and corrosion by the winds attacking the bare ground. This work, leading to the inversion of the relief, is less advanced in the basins of Tigri and Foum Aggaï than in the basin of Mekkám; it reaches its maximum in the basin of Tamlelt.

The Tigri is made up of a series of interlocking circular terraces, of gradually decreasing diameter and altitude, the lowest of which surrounds a central depression occupied by a daya. This vast basin with sheer edges and jagged contours runs roughly from east to west, at the foot of the Hauts Plateaux, and its edges are located at a fairly constant altitude, close to 1,350 m. The central depression is only at elevation 1148, and the highest point on the edges of the basin is at 1383 m. The various terraces are staged at relative altitudes of 27 m, 98 m, 117 m, 191 m and 227 m above the bottom of the central depression. A little to the west of the highest point of the peripheral ridge appears, at elevation 1373, a small volcanic apparatus, discovered by Ê.F. Gautier in 1914 [22] and, a little further N, a second that Russo described in 1927 [23,24].

2.3 Wind directions and speeds

According to the statistics concerning the frequency and the directions of the winds recorded at the Bouarfa station between 1984-1989, the wind roses are more starry indicating a predominance of the winds coming from the collateral points: SW, NW, NE [25]. In summer, the east winds are dominant. This East to SE or Chergui wind occurs most often in summer and its duration is from a few hours to a few days. It is accompanied by very high temperatures and causes a drop in the relative humidity of the air.

The Chergui can also, very exceptionally, occur in winter: the air is then dry and cold. It has a noticeable effect on the fixing vegetation of the dunes, but can also orient the nebkas in the opposite direction from their usual state.

The direction and speed of the wind are represented by the wind roses (**Figure 5**). In Bouarfa, the strong prevailing winds are from W, S and ESE. At Chott Tigri, strong winds are from directions: WNW, W and SSE (**Table 1**).

In Bouarfa, from November to April, strong SSW winds dominate. In spring and summer (May-August), strong winds from the S, SSE dominate. Finally, in September and October, strong SSW winds dominate (**Table 1**).

In Chott Tigri, from November to May, strong winds from the W and WNW dominate. In summer (June-August), strong SSE and S winds dominate. Finally, in September and October, strong WSW winds dominate.

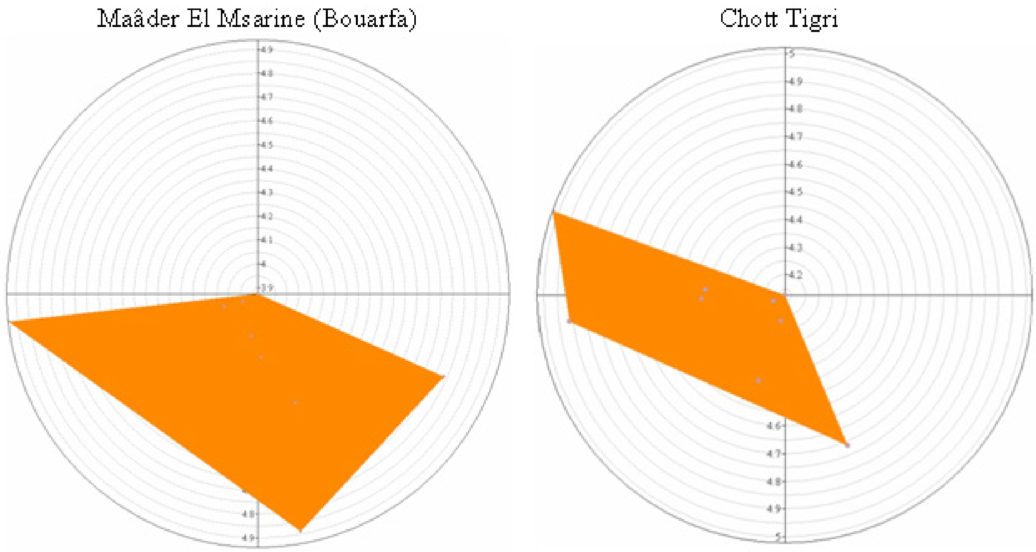


Figure 5. Wind directions and speeds (1981-2021).

Source: https://power.larc.nasa.gov/data-access-viewer/.

Table 1. Wind directions and speeds (1981-2021).

	Mader El Msarine		**Chott Tigri**	
	Wind Direction	Wind Speed (m/s)	Wind Direction	Wind Speed (m/s)
Janary	246	14.7	287	16.0
February	255	15.4	278	16.6
Mars	248	16.5	263	17.2
April	264	17.8	290	18.1
May	170	17.6	263	17.7
June	114	17.1	158	17.0
July	161	15.7	197	16.0
August	177	14.9	188	15.2
September	188	14.6	240	15.0
October	199	13.9	236	14.9
November	249	14.5	268	15.9
December	243	14.2	274	15.9

3. Materials and methods

The foundations of the GPS technique are developed in several references [26-32,15]. The GPS system is based on a constellation of 24 satellites in orbit around the Earth which continuously emit a radio signal coded on two frequencies (L1=1.2 GHz and L2=1.5 GHz). These signals are modulated on the phase by binary codes which contain information on the time, term C/A (Coarse Acquisition) or term P (Precise Acquisition). C/A signals can be used by everyone, while access to the P-code was restricted until the beginning of the year 2000 [33].

Differential GPS uses a network of fixed reference stations that transmits the difference between the positions indicated by the satellites and their known real positions. In fact, the receiver receives the difference between the pseudo-distances measured by the satellites and the true pseudo-distances and can, thus, correct its position measurements.

The acquisition of GPS data was carried out using two Leica 1200 GPS stations equipped with antennas, during nine campaigns, from 2013 to 2021. Stakes are installed on-site to serve as a reference. Sampling was done once a year. GPS receivers were powered by batteries. Several GPS measurements were made during the nine campaigns (**Figure 6**). Horizontal and vertical accuracy is less than 1 cm. The coordinate system used is Lambert North Morocco, Zone 1. During each campaign, different measurement points are surveyed following the general shape of the dune. For the profiles, the same points are measured each year per location even if it is variable.

GPS data were processed in RTK mode. The precise coordinates were calculated directly in the geodetic reference. The network formed by the "fixed" and "mobile" stations were processed by fixing the positions of the two stations. The calculations were carried out using precise orbits and taking into account the phase center variation models of the antennas. The final result is a vector: north-south component = X, east–west component = Y, Z component = altitude. The precision achieved is millimetric [34].

In the second step, the data undergo post-processing: Import and export by the Geo Office 7 software, then data processing and export in shapefile or ASCI using Covadis software from Autocad, Surfer or ArcGIS.

Figure 6. Fixed and mobile stations in the Chott Tigri. Note the pegs taken as a reference.

4. Results and discussion

4.1 Moulouya mouth

Through the monitoring of the mouth of the Moulouya, over a period extending from 2013 to 2021, we collected sowing of 5302 points. Visually, we see that the coastline has retreated 172 m on the right bank and 106 m on the left bank (**Figure 7**). As for the "pulley", it has moved to the southeast by 350 m.

4.2 South of Bouarfa

Dune 1 moved between 2013 and 2019① by 16.36 m towards the southeast. However, we can note a preferential displacement according to two components: towards the southwest: 19.06 m and towards the east: 14.51 m (**Figure 8**).

The surface and the volume evolve in parallel. We note a sharp drop in 2015 and 2019 where the volume becomes lower than the surface (**Figure 9**). It fell from 1558 m^3 in 2014 to 1099 m^3 in 2015, to reach 415 m^3 in 2019, a loss of 73%. This means that the dune has been

① The series ended in 2019 because of work to combat desertification, which consists of the fixation of dunes by vegetation.

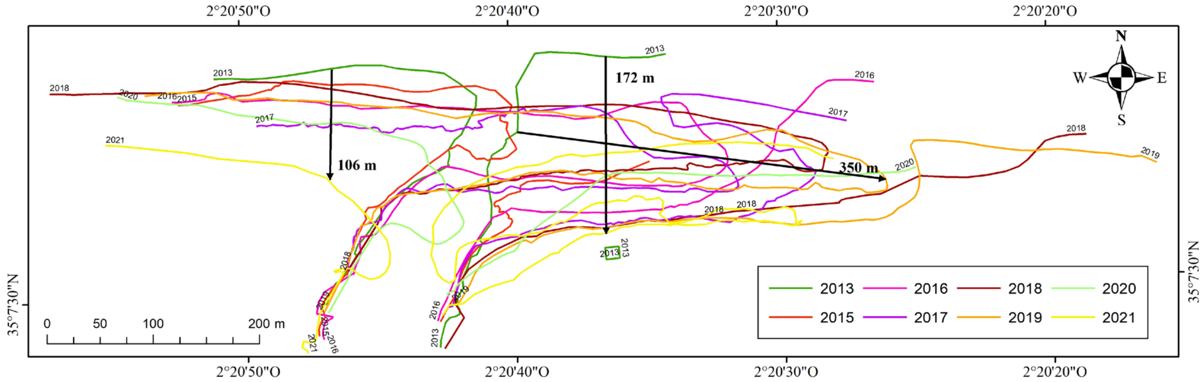


Figure 7. Moulouya mouth: Current dynamics map.

spread out and has lost its volume. The same applies to its surface area, which fell from 1,490 m^2 in 2013 to 618 m^2 in 2019, i.e. a loss of 59%.

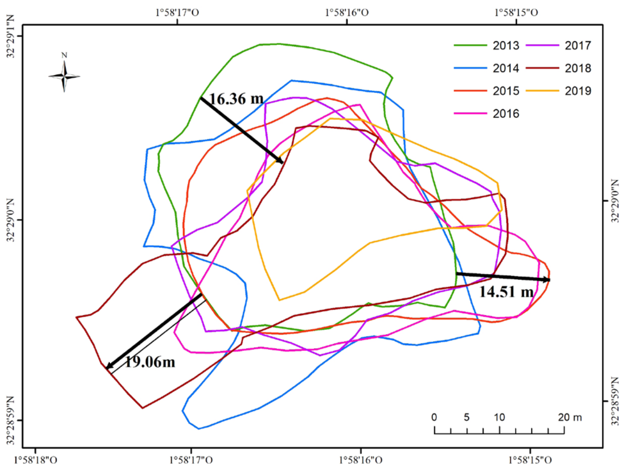


Figure 8. Evolution of the positions of dune 1 south of Bouarfa.

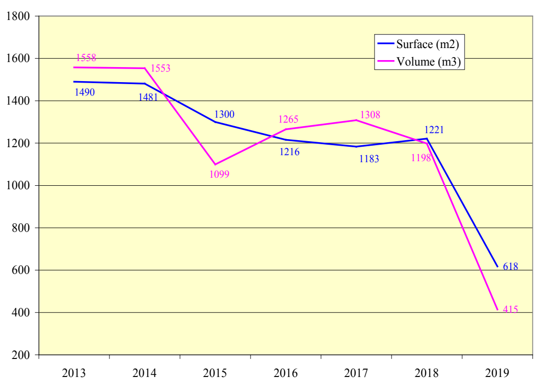


Figure 9. Variation in the surface and volume of dune 1 south of Bouarfa.

Dune 2 moved generally 25.66 m east-northeast. Nevertheless, other displacement vectors can be observed: 6.50 m to the south; 14.39 m to the southeast and 25.49 m to the north (**Figure 10**).

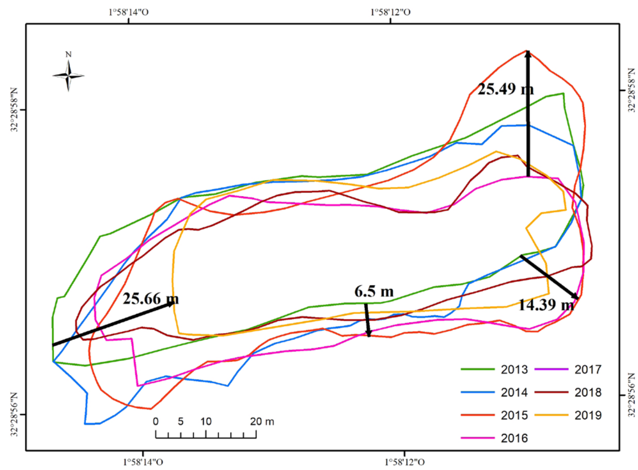


Figure 10. Evolution of the positions of dune 2 south of Bouarfa.

The comparison of the surface and the volume shows a general decreasing trend even if we note a certain increase in the surface and the volume from 2014 to 2015. The surface is often greater than the volume, except in the year 2018. However, the volume curve descends more than the surface curve. In other words, the dune is spread out and its volume is low. This behaviour is probably controlled by the dynamics of the winds which delimit compartments in differential displacement, and by the position of the dunes in relation to the topographic surface (**Figure 11**).

It can therefore be seen that the wind speeds have a significant influence on the distribution of sandy deposits in the Chott Tigri and Maâder el Msarine. Dunes form and move in the direction of the wind, but not all dunes move at the same speed: the speed decreases with the distance from the crest which marks the beginning of the dune field. As you might expect, the wind has a crucial role in moving dunes.

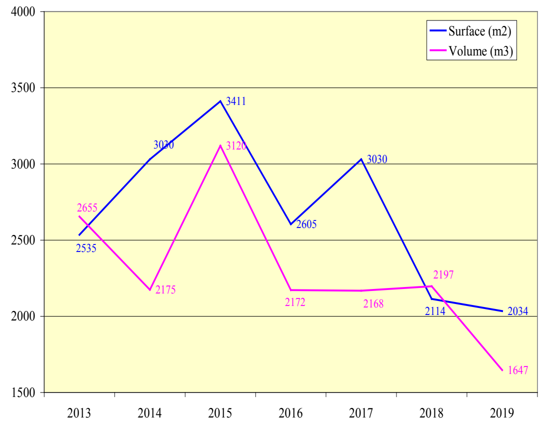


Figure 11. Variation in the surface and volume of dune 2 south of Bouarfa.

4.3 Chott Tigri

In Tigri, the general cumulative displacement of dune n°1 in 9 years of measurements is 28.95 m towards the east-northeast. However, two components can be observed: one towards the northeast: 43.11 m, another towards the east-northeast: 73.24 m and another towards the north: 15.76 (**Figure 12**).

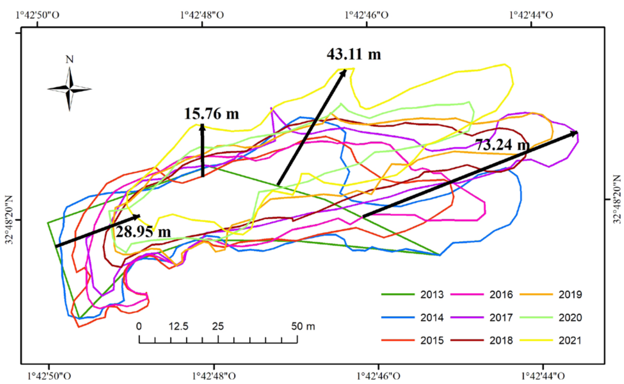


Figure 12. Evolution of the positions of dune 1 at Chott Tigri.

The surface and the volume evolve differently. The year 2014 is marked by a jump in the time series of volumes, which is particularly visible: a 100% increase compared to 2013, followed by a 36% decrease, while the surface has not changed much over the three years (**Figure 13**). This increase in volume is due to the wind, which plays a crucial role in moving the dunes.

Dune n°2 records a general movement of 79.58 m towards the east northeast (**Figure 14**).

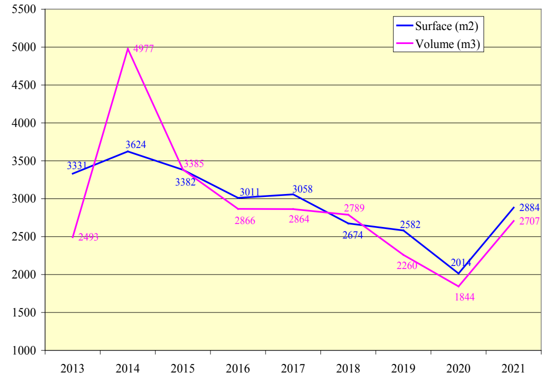


Figure 13. Variation of surface and volume of dune 1 at Chott Tigri.

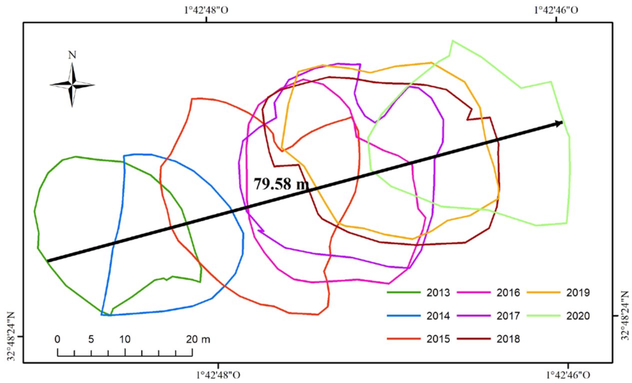


Figure 14. Evolution of the positions of dune 2 at Chott Tigri.

The surface and volume curves evolve in parallel with a general increasing trend (**Figure 15**).

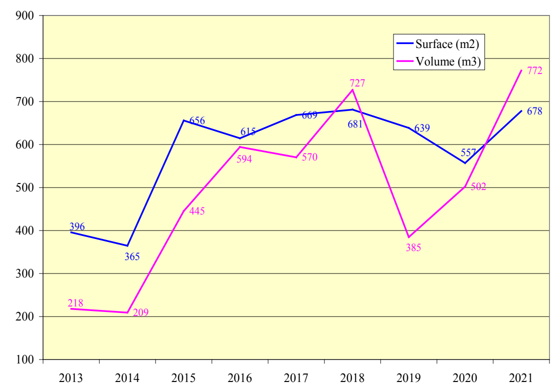


Figure 15. Variation of surface and volume of dune 2 at Chott Tigri.

The comparison between the results obtained over the years 2013 to 2021 indicates respective average speeds of 6 and 3 m/year for the dunes of Bouarfa and 5 and 10 m/year for the dunes of Tigri. These annual variations are probably due to wind speed.

The different results of this study are summarized in the following **Table 2**.

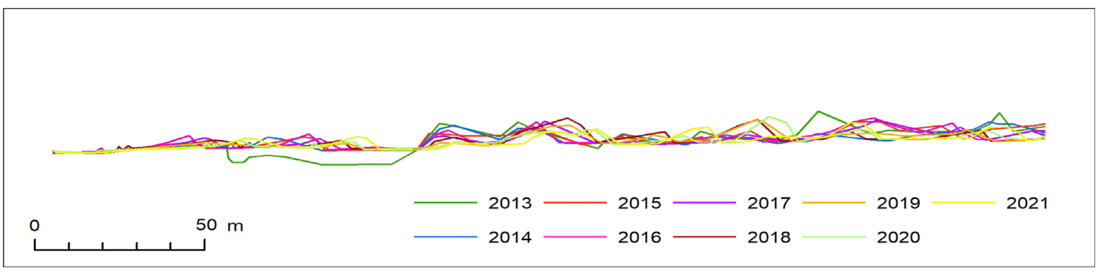
4.4 Topographic profiles

The results obtained from two micro-topographic profiles of the Chott Tigri dunes are interesting (**Figure 16**). Their comparison (2013-2021) shows significant annual changes: Erosion in some compartments and sedimentation in others. In other words, ridges have been eroded and new ones have been created. This is due to the remobilization of the sands by the wind.

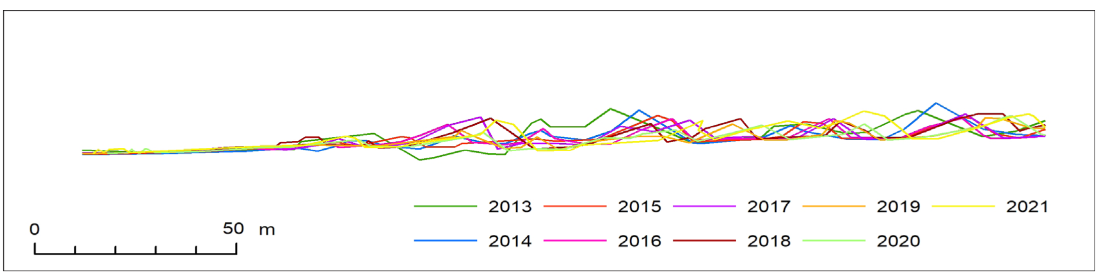
But why do the dunes slow down and change shape? This is of course due to the wind which affects the study area and carries the flow of sand.

Table 2. Synthesis of the dynamics of the coast and dunes of eastern Morocco (2013-2021).

		Retreat from the coast (m)	Displacement of the littoral spit towards the East (m)		
Moulouya mouth	Left Bank	106	350		
	Right bank	172			
		Displacement to the Southeast (m)	Displacement to the South-West (m)	Displacement to the East (m)	
Dunes south of Bouarfa	Dune 1	16.36	19.06	14.51	
		Displacement to the East-North-East (m)	Displacement to the South (m)	Displacement to the Southeast (m)	Displacement to the North (m)
	Dune 2	25.66	6.5	14.39	25.49
Dunes at Chott Tigri		Displacement to the East-North-East (m)	Displacement to the North-East (m)	Displacement to the East-North-East (m)	Displacement to the North (m)
	Dune 1	28.95	43.11	73.24	15.76
	Dune 2	79.58			



a



b

Figure 16. a. Micro-topographic evolution of the profiles of Chott Tigri (289 m) between 2013 and 2021 (site 1, scale 1 cm = 2 m); b. Micro-topographic evolution of the profiles of Chott Tigri (237 m) between 2013 and 2021 (site 2, scale 1 cm = 2 m).

Dunes create roughness, which slows down the wind. Thus, the wind pulls more sand from the first dunes, which causes the dunes to move more quickly.

The crests of the first dunes are devoid of vegetation cover. Dune movement is too rapid for plants to take root. Vegetation only appears from a hundred meters. When the dunes become slow enough, the plants settle, preferably at the ends of the dunes, or in the inter-dune corridors and help to immobilize these areas.

This type of dynamic had already been observed on coastal dunes [35] and inland, as is the case of Sand Hills in Nebraska [36].

It is our belief that a detailed time series analysis should be conducted after each storm to show the periodic variations of these dunes and their seasonal patterns. The variation of the mean hourly winds at the climatic station of Bouarfa must be correlated with the movements of these dunes.

5. Conclusions

This should clearly explain the main conclusions of the article, highlighting its importance and relevance.

GPS is therefore suitable for measuring slow movements of the shoreline and dunes. Its use in eastern Morocco is a first for the measurement and monitoring of coastal and wind dynamics. It offers the advantage of delivering three-dimensional positioning. The results obtained make it possible to quantify the 3-D kinematics of these spaces with an accuracy of a few millimeters.

The dispersion of the measurements observed, in particular for the dunes, results from the variations in the direction of the winds with a preferential movement towards the east-northeast for the Tigri and towards the southeast and north for the dunes of Maâdre El Masarine (south of Bouarfa). The measurements carried out over the years 2013 to 2021 also make it possible to highlight the spatial (compartmentalisation) and temporal (annual) variations in the kinematics of the dunes and the coastline.

The use of GPS for this type of application has been however limited due to the cost of the equipment and its maintenance. Despite these difficulties, GPS has the capacity to follow the dynamics of geomorphological entities with weak and slow movements and could therefore constitute, a warning system, a complement to conventional surveying techniques.

Author Contributions

The two authors carried out the various measurements by GPS in the field. Omar MOUADILI took care of the data processing (Covadis and ArcGis software) and the production of the maps. Abdelkader SBAI wrote the text.

Conflict of Interest

There is no conflict of interest in the publication of this article.

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References

[1] Girault, F., 1992. Auscultation de versants instables par imagerie numérique (French) [Auscultation of unstable slopes by digital imaging]. Thèse Ingénieur CNAM, Paris. 193.

[2] Weber, D., Herrmann, A., 2000. Reconstitution de l'évolution géomorphologique de versants instables par photogrammétrie numérique (French) [Reconstruction of the geomorphological evolution of unstable slopes by digital photogrammetry]. L'exemple du glissement de terrain de Super-Sauze, Bull. Soc. Géol. France. 171(6), 637-648.

[3] Fruneau, Â., Achache, J., Delacourt, C., 1996.

Observation and modelling of the Saint-Etienne-de-Tinée landslide using SAR interferometry. Tectonophysics, 265, 181-190.

[4] Mohr, J.J., Reeh, N., Madsen, S.N., 1998. Three dimensional glacial flow and surface elevation measured with radar interferometry. Nature. 391(6664), 273-276.

[5] Kimura, H., Yamaguchi, Y., 2000. Detection of landslide areas using satellite radar interferometry. Photo Grammetric Engineering and Remote Sensing. 66(3), 337-344.

[6] Bogaard, T.A., Antoine, P., Desvarreux, P., et al., 2000. The slope movements within the Mondorès graben (Drôme, France): The interaction between geology, hydrology and typology. Engineering Geology. 55(4), 297-312.

[7] Fix, R.E., Buøt, T.P., 1995. Global positioning system: An effective way to map a small area or catchment. Earth Surface Processes and Landforms. 20, 817-828.

[8] Higgit, D.L., Warbutton, J., 1999. Applications of differential GPS in upland fluvial morphology. Geomorphology. 29, 121-134.

[9] Duranthon, J.P., 2000. Application de la méthode GPS de localisation par satellite à la surveillance de sites naturels instables (French) [Application of the GPS method of satellite location to the monitoring of unstable natural sites]. Bulletin de Liaison des Laboratoires des Ponts et Chaussées, 228, 47-57.

[10] Kaplan, E., Hegarty, C., 2005. Understanding GPS—Principles and applications. Artech House: Norfolk, USA.

[11] McNamara, J., 2008. GPS for Dummies. Wiley: New York.

[12] Abulude, F.S., Akinnusotu, A., Adeyemi, A., 2015. Global positioning system and its wide applications. Continental Journal of Information Technology. 9(1), 22-32. Available from: http://www.wiloludjournal.com.

[13] Dixon, T., 1991. The global positioning system. Reviews of Geophysics. 29, 249-276.

[14] Larson, K.M., Agnew, D.C., 1991. Application of the global positioning system to crustal deformation measurement. I. Precision and accuracy. Journal of Geophysical Research Solid Earth. 96, 16547-16565.

[15] Dominguez, J.M., 2005. Topographie: découvrir le fonctionnement du GPS [Internet]. Available from: http://www.futura-sciences.com/magazines/matiere/infos/dossiers/d/physique-topographie-decouvrir-fonctionnement-gps-504/page/2/.

[16] Sbai, A., Mouadili, O., Oukada, M., et al. (editors), 2015. Apport du GPS au suivi de la dynamique littorale et éolienne. Application au Maroc nord-est (French) [Contribution of GPS to the monitoring of coastal and wind dynamics. Application in northeastern Morocco]. 21ème rencontre des géomorphologues marocains; 2015 Dec 16-17; Casablanca.

[17] Sbai, A., Mouadili, O., Saidi, A., et al. (editors), 2016. Le GPS en géomorphologie dynamique. Application au suivi de la dynamique littorale et éolienne (Maroc nord-est) (French) [GPS in dynamic geomorphology. Application to the monitoring of coastal and wind dynamics (northeast Morocco)]. La 3ème Edition du Colloque International des utilisateurs du SIG; 2016 Nov 22-23; Oujda. p. 397-403. http://www.ump.ma/fr/ouvrages/actes-du-colloque-international-des-utilisateurs-du-sig-3eme-edition. P.397-403.

[18] Sbai, A., Bouazza, A. (editors), 2002. Evolution géomorphologique et dynamique récente de la plaine littorale de Saïdia (Maroc Nord-est) (French) [Recent geomorphological and dynamic evolution of the coastal plain of Saïdia (north-eastern Morocco)]. Colloque national: Le littoral méditerranéen oriental: diagnostic et choix de développement et d'aménagement; 2002 Feb 13-14; Oujda. p. 3-30.

[19] Salmon, M., Sbai, A., Boumeaza, T., et al., 2010. The erosion of the soft coasts of the extreme north-east of Morocco. Bulletin of the Geographical Society of Liège (BSGLg). 54, 97-105.

[20] Breil, P., Combe, M., Etienne, H., et al., 1977.

Le Haut Atlas oriental. In <Ressources en Eau du Maroc> (French) [The Eastern High Atlas. "Water Resources of Morocco"]. Tome 3: Domaines atlasique et sud-atlasique. Editions du Service Géologique du Maroc. Rabat. pp. 140-159.
[21] Medioni, R., 1970. Le Chott Tigri (Hauts Plateaux du Maroc oriental) (French) [The Chott Tigri (High Plateaux of Eastern Morocco)]. Stratigraphie, tectonique et évolution morphogénétique à la lumière d'observations nouvelles. Notes Serv. Géol. Maroc. 30(225), 11-20.
[22] Gautier, E.F., 1914. Un volcan pliocène au Tigri (French) [A Pliocene volcano in Tigri]. Report of the Academy of Sciences. Séries CLI. pp. 580.
[23] Russo, P., 1927. Recherches géologiques sur le territoire des Hauts Plateaux (Maroc Sud-oriental) (French) [Geological research on the territory of the Hight Plateaus (south-eastern Morocco)]. Annales de l'Université de Lyon (N.S). 46, 197.
[24] Russo, P., 1947. La morphologie des Hauts Plateaux de l'est marocain (French) [The morphology of the high plateaus of eastern Morocco]. Annales de Géographie. 56,(301), 36-48.
[25] Sbai, A., Moussaoui, F., Oualit, N., 1992. Les régimes des vents au Maroc oriental (French) [Wind regimes in eastern Morocco]. Méditerranée. 3-4, 45-52.
[26] Leick, A., 1995. GPS satellite surveying. Wiley: New York. pp. 256.
[27] Herring, T.A., 1996. The global positioning system. Science. 96, 32-38.
[28] Hofmann-Wellenhof, B., Lichtenegger, H., Collins, J., 1997. GPS: Theory and practice, 4th Ed. Springer: New York. pp. 389.
[29] Hofmann-Wellenhof, B., Lichtenegger, H., Wasle, E., 2007. GNSS—Global navigation satellite systems: GPS, glonass, galileo, and more. Springer Science & Business Media: German. pp. 518.
[30] Hofmann-Wellenhof, B., Lichtenegger, H., Collins, J., 2013. Global positioning system: Theory and practice. Springer Science & Business Media: German.
[31] Guochang, X., 2007. GPS: Theory, algorithms and applications. Springer Science & Business Media: German. pp. 340.
[32] Chevalier, P.A., 2002. Fondements mathématiques du positionnement Par GPS. Une introduction didactique à la géométrie du GPS: 3ème partie [Internet]. Available from: http://mayer-win.free.fr/telechargement/gnss_triangulation.pdf. 21 p.
[33] Malet, J.P., Maquaire, O., Klotz, S., 2000. The Super-Sauze flowslide (Alpes-de-Haute-Provence, France); triggering mechanisms and behaviour, in: VIIIth Int. Symp., Landslides, Cardiff. Bromhead, E., Dixon, N., Ibsen, M.-L. (Eds). Proc. 8th Int. Symp. on Landslides, 2000, Cardiff. United Kingdom. P.999-1006. Landslides in Research, Theory and Practice. Proc. 8th Int. Symp. on Landslides.
[34] Gilbert, C., 1993. Portable GPS systems for mapping: Features versus benefits. Earth Observation Magazine. 10, 43-48.
[35] Sbai, A., Benata, M., Lasgaa H., 2011. La végétation des dunes littorales de la côte de Saidia —Cap de l'Eau: des écosystèmes entre nature et société (French) [The vegetation of the coastal dunes of the coast of Saidia—Cap de l'Eau: ecosystems between nature and society]. Colloque national: Systèmes environnementaux et prévision: approches et cas de figures. Université Sidi Mohammed Ben Abdellah. Fès Sais. 31 mars-1er avril 2011.
[36] Bailly, S., 2012. La migration des dunes de sable blanc, dunes du désert de White Sands, au Nouveau-Mexique [Intenet]. Pour la Science. Available from: https://www.pourlascience.fr/sd/geosciences/la-migration-des-dunes-de-sable-blanc-11248.php.

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ARTICLE

Fishing Production and Fishing Changes in Hong Kong after the Ground Trawl Ban of 31st December 2012: A Geospatial Evaluation

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ABSTRACT

From data published by the Hong Kong SAR (HKSAR) government in their two sole fisheries surveys of 2006 and 2016/2017, the current authors produced regional maps using spatial interpolation to more accurately describe and estimate the geographic coverage of changes in fishing production in Hong Kong waters since the ground trawl ban of 2012 December 31st. These suggest the fishing industry has adapted to smaller craft, and that fishing production increased in several areas in the period after the ground trawl ban came into effect. In addition, the maps enable a smoother assessment to be made of the geospatial changes in fishing production which have occurred since the ground trawl ban and suggest a 'workaround' by fishermen. In particular, small fishing craft known as *sampans* are able to take advantage by being more suitable vessels for areas such as narrower or shallower bays. Marine plastics pollution is also a proxy indicator of these activities, as evidenced by discarded fishing gear that includes plastic nets, floats, and other fishing boat equipment.

Keywords: Fishing production; Commercial fishing; Marine plastics; Ground trawl ban

1. Introduction

The purpose of this paper is to investigate the potential impacts of the 2012 ground trawl ban by using a geostatistical analysis of published government fisheries data to compare fishing production intensities before and after the ban came into effect.

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We quantify how fishing production and fishing have changed in the period between the two Hong Kong Government surveys of 2006 and 2016/2017. This is supported by additional photographic evidence from field observations of current fishing practices and discarded plastics fishing gear.

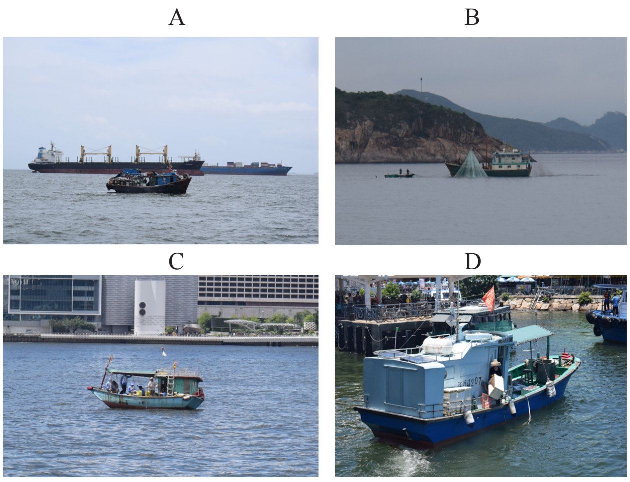

Figure 1. Field observations of recent fishing activities after the ground trawl ban of 31st December 2012 came into effect.
A. Fishing in the Lamma Channel West of Hong Kong Island: 22.24461N, 114.08899E June, 2020.
B. Banned Trawling Between Cheung Chau and Lantau Islands, Hong Kong 2020 at Northern Cheung Chau, 22.21594N, 114.03569E, June 2020.
C. Sampan Fishing in Victoria Harbour, Hong Kong at Hong Kong Island and the Southern Kowloon Peninsula: 22.29272N, 114.17226E, June 2020.
D. Polystyrene Foam Boxes Used in Local Sampan Fishing, Cheung Chau Island Public Pier, June 2020: 22.20798N, 114.02813E.

The Hong Kong Government has implemented a series of fisheries management measures for the conservation of marine resources and the promotion of sustainable development of the fishing industry. Alongside the prohibition of destructive fishing practices including a statutory ban on trawling in Hong Kong waters starting on 31 December 2012 (AFCD, 2022), other management measures were implemented, including the surveying and registration of local fishing vessels. Since the ground trawl ban, changes in fishing activity in Hong Kong have largely shifted from inshore and coastal trawling to line fishing by sampan (i.e., Class III vessels typically smaller than 15 m in length①) [1] as shown in **Figures 1A and 1D** alongside catches by shrimp boats, although trawling does continue in places. This may also be occurring unofficially as evidenced by these vessels turning off their navigational information transponders during nighttime trawls, which the authors have been able to confirm on shipping applications such as *ship-tracker*② [2] (see **Figure 1B**). Here, vessel monitoring system (VMS) technology has the potential to provide data as it has done for the offshore fleet but has yet to be applied in relation to inshore fishing [3]. Moreover, fisheries evaluation is made difficult by a scattered fishing effort, especially on large islands with remote fishing harbours [4], which is precisely the physical geography of the Hong Kong fisheries evaluated in this paper.

2. Geostatistical mapping of fishing production

We obtained spatial fisheries production data from the only two extensive Hong Kong Government surveys, which were performed in 2006 and 2016/2017, in which 720-hectare rectangular quadrat representative point sample values of fish caught were provided across the entire Hong Kong regional offshore region [5]. The survey sampling design employed a contiguous rectangular grid lattice with each grid rectangle covering 720 hectares and which covered the entire Hong Kong marine domain as defined in the Hong Kong Government Port Survey reports. We retained this grid in order to analyse the data consistently within all the generated maps. Both the Port Surveys of 2006 and 2016/2017 were conducted via interviews to collect information from local fishermen regarding their fishing operations and fisheries production. The sampling response covered the various types of local fishing vessels from different homeports and based on the information reported, the geographical distribution and levels of fishing operations and fisheries production were recorded.

These datasets were imported into a geostatisti-

① Hong Kong SAR 2013 Fisheries Homeport Interview Survey Findings [1].
② Marine Traffic [2].

cal model employing ordinary kriging to interpolate between the sample point locations and generate geospatial fishing production maps for the Hong Kong Special Administrative Region (HKSAR) marine domain from GADM [6]. Geostatistical models have previously been used by the authors to enable geospatial metrics of interest to be interpolated on a regional basis in a wide variety of contexts, ranging from epidemiology to marine plastics pollution in order to enhance data visualization and estimation accuracy [7-9]. Ordinary kriging③ is a widely employed spatial interpolative method that gives the best linear unbiased estimate of the quantity at any location [10], based on the data collected from sample sites [11] (and see **Appendix 1** to **3**).

Ordinary kriging was thus employed here to produce separate maps of estimated fishing production for the years 2006 and 2016/2017, namely before and after the ground trawl ban of 2012 as shown below in **Figure 2**.

In terms of fishing production from all vessel types, the map based on 2006 data shown in **Figure 2A**, clearly implies that the highest fishing intensities were centred around the fishing ports and communities located in the outlying islands west of Hong Kong at Cheung Chau, Peng Chau, southwestern Lantau and northeast Lantau adjacent Tsing Yi to the north-west of Hong Kong Island. To the north, on the mainland side of Hong Kong, the bays of Pan Long Wan, and Sai Kung, Plover Cove in the northeast, and Double Island adjacent to mainland China also showed higher fishing productivity. A comparison of this map with the corresponding map for 2016/2017 as shown in **Figure 2B**, distinguished by an overall bluer coloration, clearly shows that there was an overall decrease in regional production. However, the latter map also revealed that despite the overall decrease, some areas still experienced an increase in fisheries production. Although production decreased in designated key marine protected areas after the trawl ban came into effect, our maps suggest that fishing intensity elsewhere, especially from smaller vessels such as sampans, increased in several inshore areas, thus posing concomitant environmental impacts. This is verified by a direct comparison of **Figure 2C** with **Figure 2D** showing the respective productions for sampans in 2006 and 2016/2017.

These fishing production changes are more clearly shown by change-in-fishing-production maps, which are shown in **Figure 3**, and were obtained by taking the differences in production between the respective geospatial maps of **Figure 2**. In the maps of **Figure 3**, areas of increased fishing production are shown in red and appear most noticeably around Lantau-island in the south and the channels located between marine protected areas in the southern waters such as that between Cheng Chau and Lamma Island.

In the map shown in **Figure 3D**, for 2016/2017, showing production changes for sampans, we could see that the higher intensity areas (shown in red) in this map corresponded reasonably well with those of **Figure 3A**, for all vessel types. Taken together these imply that since the trawling ban of 2012, fishermen have adapted to smaller craft such as sampans with a shift of fishing zones into the above areas and moreover with continuing widespread fish catches.

In particular, our sampan production change map shows clearly that sampan fishing increased in the period from 2006 to 2016/2017. This can be seen by the red colouration that represents increases mapped around Lantau Island and Cheung Chau in the southwest and Cape De Aguilar in the southeast, some of these overlapping with marine protected areas. These increases are also particularly apparent in the northeastern bays and inlets of Hong Kong waters around Hong Kong's New Territories adjacent to Plover Cover and Grass Island. This is further reinforced in the southern areas by the fact that they hold large community ports for the smaller Hong Kong fishing vessels (sampans) and indeed some of the larger ocean-going trawlers, for example shrimp boats that can also be seen fishing in southern waters. **Tables 1 and 2** below summarize quantitatively the estimated fish production and changes for all vessel types

③ Kriging is a multistep process; it includes exploratory statistical analysis of the data, variogram modeling, creating the surface, and exploring a variance surface [10].

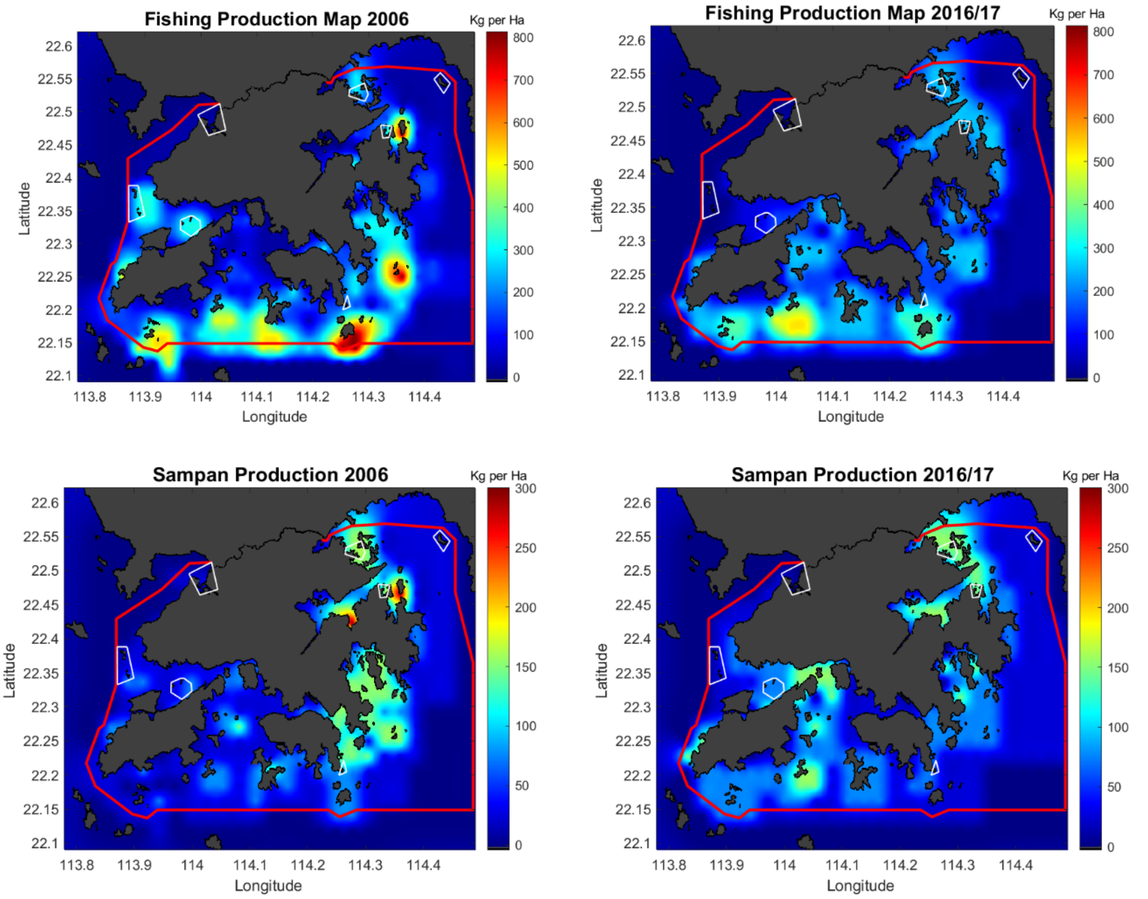

Figure 2. Fishing production maps for all vessel types and sampans in Hong Kong water, shown in kg per hectare by the colour scale on the right of each map. Maps were derived by geostatistical interpolation with ordinary kriging from data collected by the Port Surveys of 2006 and 2016/2017 [5]. Marine protected areas are highlighted (white boundary lines) and the HKSAR maritime boundary is superimposed (solid red). Scale 1:500000.

A. (Top left). Fishing Production from all vessel types in Hong Kong 2006, (scale 0 to 800 kg per hectare),

B. (Top right). Fishing Production from all vessel types in Hong Kong 2016/2017, (scale 0 to 800 kg per hectare).

C. (Bottom left). Fishing Production from sampan small boat fishing in Hong Kong 2006, (scale 0 to 300 kg per hectare).

D. (Bottom right). Fishing Production from sampan small boat fishing in Hong Kong 2016/2017, (scale 0 to 300 kg per hectare).

compared with sampans based on data for the two HKSAR surveys in 2006 and 2016/2017.

The fishing change maps of **Figures 2 and 3**, thus present a novel data visualization of the HKSAR government fishing surveys of 2006 and 2016/2017 for identifying changes in fisheries production.

Table 1, shown above summarizes the raw data based on 720-hectare quadrat tonnage, whilst **Table 2**, summarizes fishing production based on the interpolated data pixel tonnage, obtained from kriged values extracted from the maps in **Figure 2**. It can be seen that the kriged estimates in **Table 2**, are consistently below those estimated from raw data in **Table 1**, due to statistical smoothing from kriging interpolation and restriction to map values lying strictly within the HKSAR maritime boundary limits. Based on the raw data extracted from the HKSAR surveys, **Table 1**, thus shows that sampan fishing as measured in 2016/2017 had indeed increased after 2006 in terms of the regional area fished (measured in 720-hectare quadrats) and in fishing production tonnage of fish landed. Specifically, the number of quadrats fished by sampans increased by 11% while the estimated tonnage of fish they landed increased by 16% (1,980 tonnes). These values contrast markedly when compared with the fishing changes recorded for all vessel

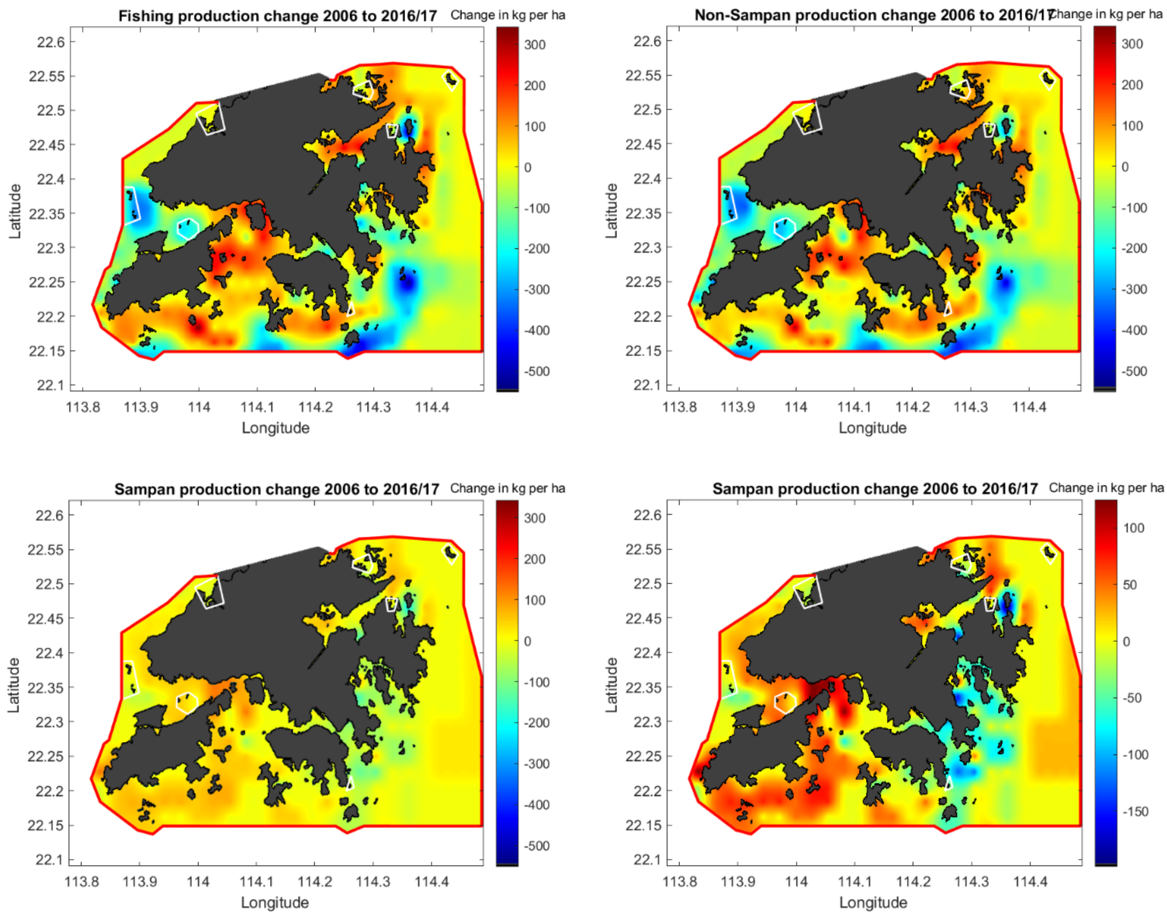

Figure 3. Comparison of change in fishing production [kg per hectare] for all vessel types, non-Sampans, and Sampans within the HKSAR maritime region (solid red line) for the survey periods of 2006 and 2016/2017. Marine protected areas are superimposed (solid white lines). Scale 1:500000.

A. (Top left). Overall fishing production change based on catch taken from all vessel types.

B. (Top right). Fishing production change based on catch taken from vessels other than sampans.

C. (Bottom left). Fishing production change based on catch taken from sampans.

D. (Bottom right). Fishing production change in C, with rescaled colouring for greater contrast.

Table 1. Estimated fishing production changes in the Hong Kong maritime region occurring in the period between 2006 and 2016/2017 based on the HKSAR surveys raw data (summarized from Appendix 4, Tables A1 to A4).

Estimated Fishing Change between surveys	Number of quadrats fished			Total fishing production (tonnes)		
	2006	2016/17	% Change	2006	2016/17	% Change
All vessels	313	291	–7.02	36,504	30,744	–15.77
Sampans	267	296	10.86	10,980	12,960	15.57
Sampans production proportion %	-	-	-	30.80	41.28	-

Table 2. Estimated fishing production changes strictly within the HKSAR maritime boundary in the period between 2006 and 2016/2017 based on the spatial interpolative fishing production change maps of Figure 2.

Estimated Fishing Change	Total fishing production (tonnes)		
vessel type	2006	2016/2017	% Change
All	27,969	21,479	–23.20
Sampans	7,016	8,381	19.46
% Sampans/All	25.08	39.02	

types, which respectively *decreased* by 7% in terms of the area fished and 16% (5,760 tonnes) in terms of their production tonnage.

Table 2, further provides more accurate estimates from kriging for fishing production, which concur with the directional changes (increase/decrease) observed for each respective **Table 1** quantity, but also suggest that the respective production changes are greater. In particular, from 2006 to 2016/2017 the production from all vessel types decreased by 23% (by 6,490 tonnes) while sampan production increased by 19% (by 1,365 tonnes) thereby rising from 25% to 39% of the respective total fishing production in each measured year.

Figure 4 below provides a further visualization of these datasets, here in terms of empirical distributions. These plots show estimated production changes based on the pixel value counts, where a pixel is defined as the unit square of area 1.2554 hectares (ha) at the GADM [6] map resolution, determined for each map of **Figure 3**. They again exhibit the overall increase in production for sampans (see **Figure 4B**) in contrast with the overall decrease for all vessel types (see **Figure 4A**) through histograms of pixel counts extracted from the respective geospatial fishing production maps of **Figure 3**. The histogram bars are shaded green (or yellow) for positive (or negative) contributions with the respective cumulative distributions achieved by summation of these bars shown in **Figures 4C and 4D**. These latter graph areas are shaded red (or black) to indicate a negative (or positive) cumulative production value. For sampans the

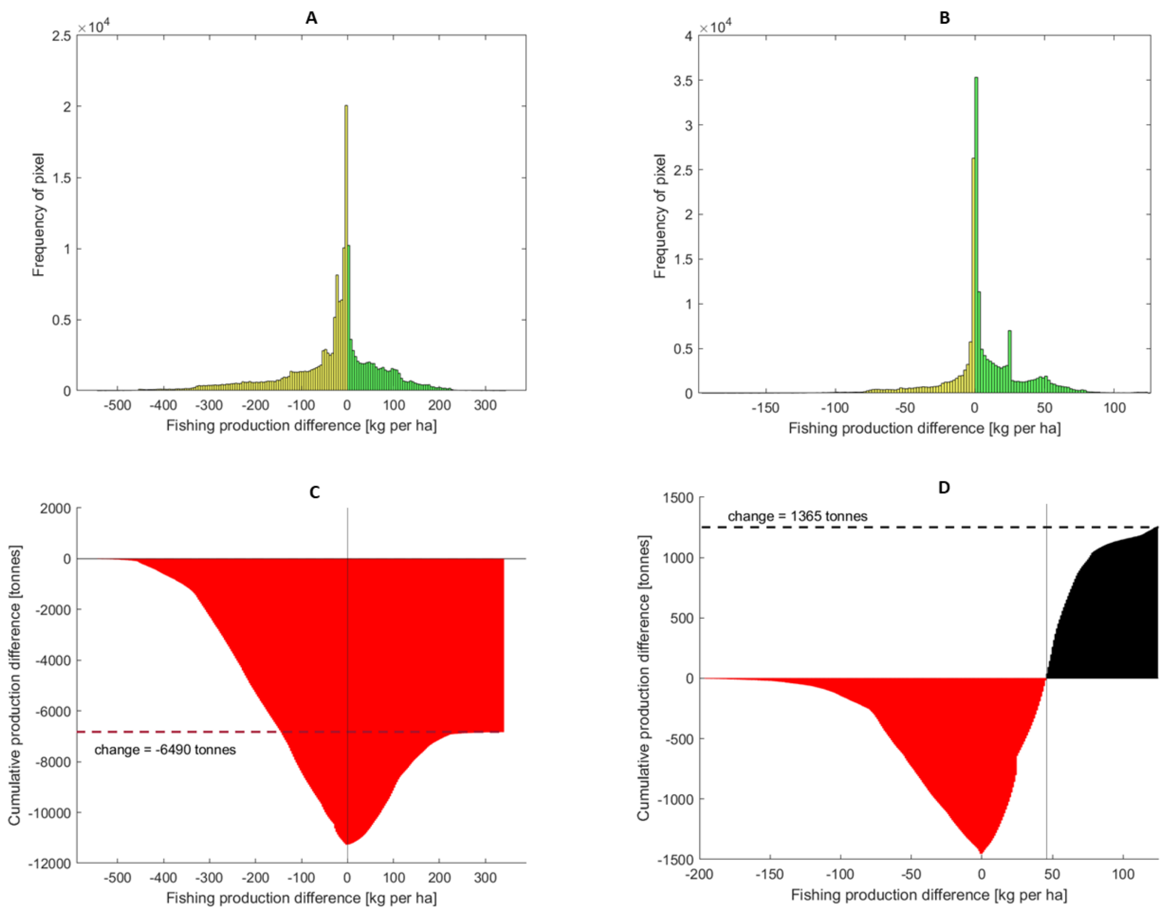

Figure 4. Estimated fishing production changes in the period 2006 to 2016/2017 strictly within the HKSAR maritime boundary. The plots compare sampans catch tonnage (B and D) with tonnage from all vessel types (A and C) based on distributions of pixel value frequencies in the interpolative maps obtained with kriging of Figure 3. In (A and B) histogram bars are shaded green (yellow) indicating positive (negative) contributions, in (C and D) cumulative total production plot areas are shaded black (red) indicating positive (negative) cumulative totals across the kriged map surface. Fishing production from sampans increased by 1365 tonnes, while all vessel types decreased by 6490 tonnes.

overall production increase is clearly seen by the cumulative curve rising above zero into the black, whilst that for all vessel types always remains well within the red.

These changes in fishing production and fishing practice are supported by the observed presence of shrimp boats in large numbers in the southern waters, perhaps replacing the heavier catches of the ground trawlers banned locally in 2012. **Table 3** below also shows that the number of fishing sampans jumped most markedly by 402 vessels in 2013 from 2012 (402 = 1604–1184) immediately after the ground trawl ban came into effect and continued to increase, reaching a peak number of 1,997 vessels in 2015, but decreasing only slightly in 2016 when the second port survey was undertaken. Likewise, outboard open sampan fishing boats were at their peak in 2012 at 2,835 vessels which had only decreased slightly to 2,617 boats by the time of 2016/2017 port survey. Notably since the 2012 ground trawl ban, all other fishing vessels had decreased from their peak of 2,208 in 2011 to 1,997 by 2016. These datasets, extracted from the Hong Kong Marine Department's data on licensed vessels therefore provide further evidence of a shift towards inshore sampan fishing activity since the ground trawl ban took effect.

3. Field observations of sampan fishing boat activity and plastics gear

We conducted field observations of selected outlying islands, coastal and inner harbour sites of the Hong Kong marine area. The sites were selected on the basis of their proximity to sampan fishing activity with the locations selected for scoping environmental impact at a central point between Hong Kong's marine parks, reserves, protected, and priority areas④ [13], such as those of south-east Lamma and Lantau Islands. On a regional basis these locations are in the environs where the ground trawl ban would be expected to have the most impact. The locations of these sites are shown in the regional map of Hong Kong in **Figure 5** below.

Table 3. Relevant types and estimated numbers of local fishing vessels by 2017.

Class III	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
Fish Carrier	2	2	3	19	21	17	23	25	26	31
Fishing Sampan	911	859	865	846	922	1184	1604	1958	1997	1982
Fishing Vessel	1922	1791	2122	2126	2208	2166	2137	2003	2030	1997
Outboard Open Sampan	2654	2550	2559	2580	2698	2835	2772	2613	2575	2621
Total	5489	5202	5549	5571	5849	6202	6536	6599	6628	6631

Figure 5. Map of Hong Kong Selected Site locations.

Source. GeoInfo Map [14], URL: https://www.map.gov.hk/gm/ Scale 1: 200000.

④ Marine Protected Areas in Hong Kong [13].

The results of this visual plastics survey are summarized qualitatively in **Table 4** below and shown with two typical sample photos of our field observations.

We found that the types of plastic debris identified could almost always be associated with sampan fishing activity and included: Plastic Fishing Line, Plastic Fishing Nets, Plastic Fishing Net Floats (see **Figure 6D**), Polystyrene Boxes and floats (a significant source of local microplastics pollution—**Figures 6C and 6B**), Polypropylene Rope, Plastic Fuel or Water Drums, and Discarded Plastic Bottles.

Thus, it could be verified through field observation that plastic-based fisheries equipment is used not only for netting materials, but also for traps, floats, dredges and lines, as well as for boat construction and maintenance, fish hold insulation and fish crates. Containers made with polystyrene foam in Hong Kong as elsewhere are ubiquitous because they are cheap, lightweight and water and thermal resistant [15,8]. Although at a global scale, fishing gear is estimated to compose less than 10% of total marine debris by volume [16], the degree of plastic fishing gear occurrence can be highly variable at smaller spatial scales when based on locality [17]. The impacts of marine debris (also known as *abandoned, lost or otherwise discarded fishing gear* (ALDFG), see **Figures 6B, 6C, and 6D**) derived from fisheries are particularly concerning in remote areas of Hong Kong and outlying islands, such as seen on Cheung Chau and Peng Chau coastlines as exhibited in **Table 4** and **Figure 6**.

Table 4. Typical sampan fishing plastics found washed up on Hong Kong Beaches.

Typical Fishing Boat Discarded Plastics* Found on Hong Kong Beaches 10th of June 2020

Sampan With Plastic Fishing Gear Types 28 March 2022

Type	Plastic Fishing Line	Plastic Fishing Nets	Plastic Fishing Net Floats	Plastic Buckets
Condition	Whole or in part	Broken or Discards	Broken or still attached to Nets	Whole or in fragments
Type	*Polystyrene Boxes	*Polypropylene Rope	Plastic Fuel or Water Drums	*Discarded Plastic Bottles
Condition	Whole, broken usually as microplastics	Whole or in pieces	Whole or in fragments	Bottles and or bottle-caps, and microplastics
Type	*Polystyrene Floats			
Condition	Whole, broken usually as microplastics			

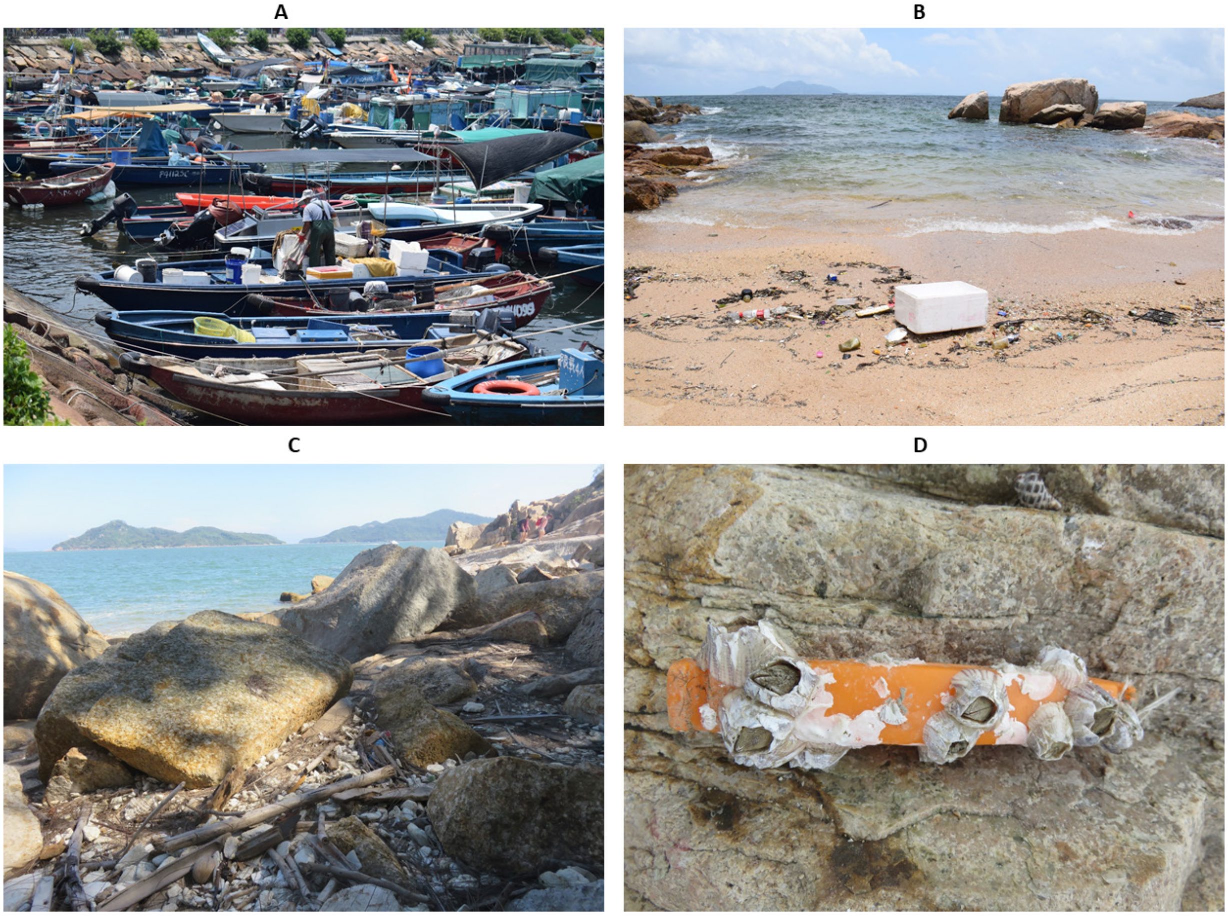

Figure 6. A. Sampans with Polystyrene Foam Boxes and Floats at Cheung Chau Island Harbour, August 2020: 22.21014N, 114.02827E. B. Discarded Polystyrene Foam Box and Microplastics Pollution at Nam Tam Bay, Southern Cheung Chau Island, September 2020: 22.20342N, 114.03379E. C. Polystyrene Foam Box Breakup Pollution, a cause of microplastics pollution, South-eastern Peng Chau Island, May 2018: 22.2836N, 114.04709E. D. Barnacles attached to plastic fishing net float at South-eastern Peng Chau Island, April 2018: 22.28105N, 114.04523E. Typically, in most transects of marine plastics described elsewhere, negative MP gradients were observed from nearshore to offshore, which showed that coastal fishing, alongside tourism, and rivers were the main sources of marine plastics in inshore coastlines [18].

4. Discussion

The fishing production and fishing change map produced in this paper from HKSAR government fishery survey raw data, provide a handle on assessing the possible impacts of the 2012 ground trawl ban. They highlight two key findings:

(1) fishing production by all vessel types had dropped by 2016/2017, meaning there were overall fewer areas being fished than in 2006 and overall fishing production also decreased.

(2) fishing production by sampans had increased by 2016/2017 and the number of areas being fished similarly increased.

These results are consistent with our hypothesis that by adapting to smaller fishing vessels (sampans), fishing production and by implication the environmental impact from discarded plastics emanating from these vessels probably increased after the 2012 ground trawl ban. These changes in fishing production were evidenced in the fishing production changes maps shown in **Figure 3**, which demonstrate that fishing production intensified markedly in some areas after the ground trawl ban came into effect. From this, it could be speculated that sampans were taking advantage of the situation as more suitable vessels for those areas (e.g., narrower, shallower bays) which is also supported by the greater plastics pollution likely from their activities resulting from increases in inshore fishing.

Whilst land-based sources of marine plastic pollution continue to gain attention, such marine-based sources are to date much less investigated [19]. The widespread incidence of *abandoned, lost or otherwise discarded fishing gear (ALDFG)* in Hong Kong calls for further investigation. Moreover, fisheries evaluation is made difficult by scattered fishing effort [4] that occurs around the Hong Kong outlying islands and remote fishing harbours often adjacent to marine protected areas. Despite laws⑤⑥ [20,21] that regulate discarding waste at sea, our field observations show that in outlying areas this legislation is not having the desired outcome. Research on fishing activity plastics in similar areas found that litter was predominantly plastic (87%) and mostly associated with fishing/boating (34%) [22]. Thus robust, quantifiable evidence of spatial and temporal patterns of inshore fishing activity is urgently required to assist management in the face of a growing number of designations of marine protected areas (MPA) [3].

Attributing plastics pollution to sources beyond empirical observations remains challenging and often contested among marine stakeholders and indeed fisheries researchers. In this context there has been increasing recognition of the need to address adverse ecological and socioeconomic effects of ALDFG particularly in urbanized coastlines⑦ [23-25] such as those of Hong Kong. Quantifying beach plastic litter worldwide through field surveys is also complicated, as plastic debris littered on inaccessible beaches might be excluded [26]. Studies of similar fishing areas in East Asia, such as those of Korea have found that operations accounted for 98.4% of the seabed litter by use, while non-fishing operations represented 1.6%. Even taking into account seasonal changes, the proportion of seabed litter from fishing operations in spring was 97.8% while that for autumn was 99.2% [27].

⑤ Hong Kong Government 1980. Dumping at Sea Ordinance (Cap. 466) 1995. Provides for control on marine dumping, and for connected purposes [20].

⑥ Hong Kong Government 1933. Summary Offences Ordinance (Cap.228) 1933: Contains provisions related to littering offences including marine littering [21].

⑦ Environmental Investigation Agency Report, April 2020 [23].

5. Conclusions

Although at the time of writing, the 2012 ground trawl ban in Hong Kong has been in effect for a decade, fishing especially from smaller boats such as sampans, remains widespread in several inshore areas. In terms of fishing catch our geostatistical maps show the highest concentrations were centred around the fishing ports and communities located in the outlying islands of Cheung Chau, Peng Chau, southwestern Lantau and northeast Lantau adjacent to Tsing Yi. Our field observations show that these local fishing communities who have their socio-economic needs met by the marine ecology appear to be lacking in commitment to conserving the very ecosystem that provides for their needs. Thus, the environmental impacts of plastics from equipment and containers used on fishing boats continue to compound the social and marine conservation challenges of widespread plastics pollution. The continuing impacts of this activity will include disturbance to the benthic and pelagic ecosystems the ground trawl ban was intended to restore. Fishery resources in Hong Kong are entirely open-access with virtually no management, except in limited areas of between 2 and 5% designated as marine parks and reserves (although fishing other than trawling, continues in marine parks under license) [28]. At the time of writing, more conventional fishery data and analytical tools are urgently required for future management alongside environmental monitoring of regular fishery activity.

6. Addressing the issues through stakeholder engagement

Because of ongoing data deficiencies on the impact of commercial fishing in Hong Kong, as of 2022 an independent fishing survey protocol by Hong Kong SAR's *Agriculture, Fisheries and Conservation Department* (AFCD) will establish a Standard Protocol for fishing surveys. This will provide data that are independent of reported catches by fishermen themselves, and establish a standard scientific protocol for the purpose of marine fishing regulation and sharing of fisheries data in Hong Kong waters [29]. Moreover, such sharing of data alongside fishing regulation may go some way to addressing the problem of marine plastics pollution and their ecological impact in this region and inform stakeholder engagement with the fishing industry and the wider marine sector. In the 2022/2023 policy address, the Hong Kong Government highlighted the importance of setting up a *"Holistic Nature Conservation Policy"* bringing together conservation and development, rather than treating them as competing goals. This policy aligned with China's 14th Five-Year Plan, Greater Bay Area Policy Areas, and the current draft of the Post-2020 Global Biodiversity Framework [30]. In response, the Worldwide Wildlife Fund [31] has called on policymakers to "…*strengthen measures to eradicate illegal fishing, including stronger collaboration between government agencies, cross-boundary collaboration with mainland China*".

In addition, to enhance fisheries management, this should include developing an Automated Identification System (AIS) to monitor fishing activities within Hong Kong and across the mainland maritime boundary. This would establish a reporting system to not only address the uncertainties in changing fisheries activity, but also address their environmental impacts. Moreover, because currently as of 2023, only 5% of Hong Kong's waters are designated as MPAs, conservationists have called for these to undergo a science-based planning exercise to include no-take reserves, Fisheries Protection Areas (FPA)s, species-specific conservation zones, community-based fisheries reserves, and other MPA designations [31]. Under the Hong Kong Government's proposed Holistic Nature Conservation Policy, the WWF as cited above, has thus recommended a joint stakeholder and environmental management plan to be implemented in all MPAs and proposed FPAs to conserve the marine ecology. We concur that this should consist of appropriate zoning and practices, including strict no-take zones and enforcing sustainable fishery practices. That would likely include controls on fishing gear discards and other plastics in a wider improved fisheries management.

Author Contributions

Alastor M. Coleby: Conceptualization, Data curation, Photography, Validation, Writing-original draft, review and editing. Eric P.M. Grist: Conceptualization, Data curation and visualization, Statistics, Modelling, Validation, writing-review and editing.

Conflict of Interest

There is no conflict of interest.

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References

[1] Macdonald, M., 2014. Expansion of Hong Kong International Airport into a Three-Runway System Environmental Impact Assessment Report Appendix 14.4 Fisheries Homeport Interview Survey Findings [Internet]. Appendix 14.4 Fisheries Homeport Interview Survey Findings [cited 2022 Aug 12]. Available from: https://www.epd.gov.hk/eia/register/report/eiareport/eia_2232014/html/Appendix%2014.4%20Fisheries%20Homeport%20Findings%20(with%20Annexes).pdf.

[2] Marine Traffic [Internet] [cited 2020 Jun 7]. Available from: https://www.marinetraffic.com/en/ais/home/centerx:114.095/centery:22.235/zoom:12.

[3] Birchenough, S.E., Cooper, P.A., Charles, A., 2021. Vessel monitoring systems as a tool for mapping fishing effort for a small inshore fishery operating within a marine protected area.

Marine Policy. 124, 104325.

[4] Bousquet, C., Bouet, M., Patrissi, M., et al., 2022. Assessment of catch composition, production and fishing effort of small-scale fisheries: The case study of Corsica Island (Mediterranean Sea). Ocean & Coastal Management. 218, 105998.

[5] Hong Kong Government, 2022. Agriculture, Fisheries and Conservation Department Port Survey 2016/2017 [Internet]. Available from: https://www.afcd.gov.hk/english/fisheries/fish_cap/fish_cap_latest/fish_cap_latest.html.

[6] GADM, 2015. Database of Global Administrative Areas [Internet]. Available from: www.gadm.org.

[7] Grist, E.P.M., 2022. 'Spread' of artemisinin resistance in Myanmar revisited. International Journal of Tropical Disease & Health. 43(15), 1-16. doi: 10.9734/ijtdh/2022/v43i1530643.

[8] Coleby. A.M., Grist, E.P.M., 2019. Prioritized area mapping for multiple stakeholders through geospatial modelling: A focus on marine plastics pollution in Hong Kong. Ocean and Coastal Management. 171, 131-141.

[9] Grist, E.P.M., Coleby, A.M., 2020. A geostatistical approach to joint stakeholder prioritization for tackling marine plastics pollution in Hong Kong. Marine Pollution Bulletin. 157, 111268.

[10] ESRI, 2022. ArcGIS for Desktop, ArcMap. How Kriging works [Internet] [cited 2022 Nov 3]. Available from: https://desktop.arcgis.com/en/arcmap/10.3/tools/3d-analyst-toolbox/how-kriging-works.htm#:~:text=Kriging%20is%20a%20multistep%20process,directional%20bias%20in%20the%20data.

[11] Cressie, N., 2015. Statistics for spatial data, revised edition. Wiley: New York. pp. 105-209.

[12] Hong Kong Government, Marine Department, 2017. Hong Kong Licensed Vessels (as at Year End) [Internet] [cited 2022 Oct 31]. Available from: https://www.mardep.gov.hk/en/fact/pdf/portstat_2_y_e3.pdf.

[13] World Wildlife Fund (WWF), Hong Kong, 2022. Marine Protected Areas [Internet] [cited 200 Apr 21]. Available from: https://www.wwf.org.hk/en/oceans/protection/.

[14] Hong Kong Government, 2022. GeoInfo Map [Internet] [cited 2022 Mar 21]. Available from: https://www.map.gov.hk/gm/ Date.

[15] Cheung, P.K., Fok, L., Hung, P.L., et al., 2018. Spatio-temporal comparison of neustonic microplastic density in Hong Kong waters under the influence of the Pearl River Estuary. Science of the Total Environment. 628, 731-739.

[16] World Wildlife Fund (WWF), 2020. Stop Ghost Gear. The Deadliest Form of Marine Plastics [Internet] [cited 2021 Nov 16]. Available from: https://europe.nxtbook.com/nxteu/wwfintl/ghost_gear_report/index.php#/p/1.

[17] Gilman, E., Chopin, F., Suuronen, P., et al., 2016. Abandoned, lost and discarded gillnets and trammel nets: Methods to estimate ghost fishing mortality, and the status of regional monitoring and management, FAO. FAO Fisheries and Aquaculture Technical Paper No. 600. Available from: https://www.researchgate.net/publication/290998244_Abandoned_Lost_and_Discarded_Gillnets_and_Trammel_Nets_Methods_to_Estimate_Ghost_Fishing_Mortality_and_Status_of_Regional_Monitoring_and_Management.

[18] Manbohi, A., Rahnama, R., Dehbandi, R., et al., 2021. Spatial distribution of microplastics in sandy beach and inshore-offshore sediments of the southern Caspian Sea. Marine Pollution Bulletin. 169, 112578.

[19] Wright, L.S., Napper, I.E., Thompson, R.C., 2022. Potential microplastic release from beached fishing gear in Great Britain's region of highest fishing litter density. Marine Pollution Bulletin. 173(Part B), 113115.

[20] Hong Kong Government, 1980. Dumping at Sea Ordinance (Cap. 466) [Internet] [cited 2022 Aug 12]. Available from: https://www.epd.gov.hk/epd/english/laws_regulations/envir_legislation/leg_waste.html.

[21] Hong Kong Government, 1933. Summary Offences Ordinance (Cap. 228) [Internet]. Con-

tains Provisions Related to Littering Offences Including Marine Littering [cited 2022 Aug 12]. Available from: https://www.epd.gov.hk/epd/english/laws_regulations/envir_legislation/leg_waste.html.

[22] Davies, L., Kemp, A., O'Loughlin, C., et al., 2022. Is conscientious beachcombing the key to 'unlock' marine plastic pollution trends through citizen science? A case study from Cockburn Sound, Western Australia. Marine Pollution Bulletin. 177, 113519.

[23] Environmental Investigation Agency Report, 2020. Nothing Fishy About It: Meaningful Measures on Fishing Gear at IMO [Internet] [cited 2022 Aug 12]. Available from: https://eia-international.org/wp-content/uploads/EIA-report-Nothing-Fishy-About-It-IMO-Briefing-single-pages-for-print.pdf.

[24] Gilman, E., Humberstone, J., Wilson, J.R., et al., 2022. Matching fishery-specific drivers of abandoned, lost and discarded fishing gear to relevant interventions. Marine Policy. 141, 105097.

[25] Gajanur, A.R., Jaafar, Z., 2022. Abandoned, lost, or discarded fishing gear at urban coastlines. Marine Pollution Bulletin. 175, 113341.

[26] Isobe, A., Iwasaki, S., 2022. The fate of missing ocean plastics: Are they just a marine environmental problem? Science of the Total Environment. 825, 153935.

[27] Song, S.H., Lee, H.W., Kim, J.N., et al., 2022. First observation and effect of fishery of seabed litter on sea bed by trawl survey Korea waters. Marine Pollution Bulletin. 170, 112228.

[28] Cheung, W.W.L., Sadovy, Y., 2004. Retrospective evaluation of data-limited fisheries: A case from Hong Kong article. Reviews in Fish Biology and Fisheries. 14, 181-206.

[29] Leung, K.M.Y., 2022, City university of Hong Kong. Workshop on Marine Spatial Planning in Hong Kong—Insights from EU Countries and the Way Forward for Hong Kong [Internet]. BECoME [cited 2021 Jan 7]. Available from: https://www.cityu.edu.hk/sklmp/news/events/become-2022.

[30] Hong Kong Government, 2022. The Natural Resources & Nature Conservation Policy in Hong Kong. [Internet] [cited 2023 Jan 11]. Available from: https://www.gov.hk/en/residents/environment/conservation/naturalresourceconservation.htm.

[31] World Wildlife Fund (WWF), 2022. WWF-Hong Kong 2022-23 Policy Address Recommendation: A Holistics Nature Conservation Policy for Sustainable Development [Internet] [cited 11 January 2023]. Available from: https://wwfhk.awsassets.panda.org/downloads/wf_hong_kong_2022_23_policy_address_recommendation_eng.pdf.

[32] Wackernagel, H., 1995. Multivariate geostatistics: An introduction with applications. Springer-Verlag: Berlin. pp. 256.

[33] The Math Works, Inc., 2019. MATLAB. Version 2019b. Computer Software. Available from: www.mathworks.com/.

[34] Hunter, G., Lowell, K. (editors), 2002. Is the ordinary kriging variance a proper measure of interpolation error? Proceedings of the Fifth International Symposium on Spatial Accuracy Assessment in Natural Resources and Environmental Sciences; Australia: RMIT University. p. 179-186. Available from: https://hdl.handle.net/11245/1.195474.

Appendix

1. Kriging and variogram model specification

We employed ordinary kriging to generate all maps using a fitted exponential model variogram:

$$\gamma(h) = c\left[1 - exp\left(-\frac{h}{a}\right)\right] \quad \text{(A1)}$$

where *γ(h)* is the semi-variance, *h* is the lag distance and *c* (the 'sill') and *a* ('the range') are the constants determined for the given data set, here by using the *Nelder-Mead simplex* direct search method [32]. The choice of exponential variogram model provided the best fit to the empirical variogram data in all cases and as an unbounded model also verified isotropy and strong spatial autocorrelation in the data by demonstrating the achievement of the sill within a finite range, as exhibited in the accompanying variogram plots below. All maps and calculations were performed using MATLAB software [33].

2. Variogram plots

The assumptions of stationarity and isotropy underlying ordinary kriging are verified by inspecting the empirical variogram and checking this is bounded by the achievement of a sill at a finite range, which is confirmed in all the variograms generated and fitted with the exponential model shown here in **Figure A1**. This shows respective empirical variograms with n = 50 bins, (black squares) with a fitted exponential model (solid red line) and the sill that is converged to (dashed blue line) corresponding to each of the fishing production maps of **Figure 2**, generated from survey data for: (top left) all vessels 2006; (top right) all vessels 2016/2017; (bottom left) sampans 2006; (bottom right) sampans 2016/2017.

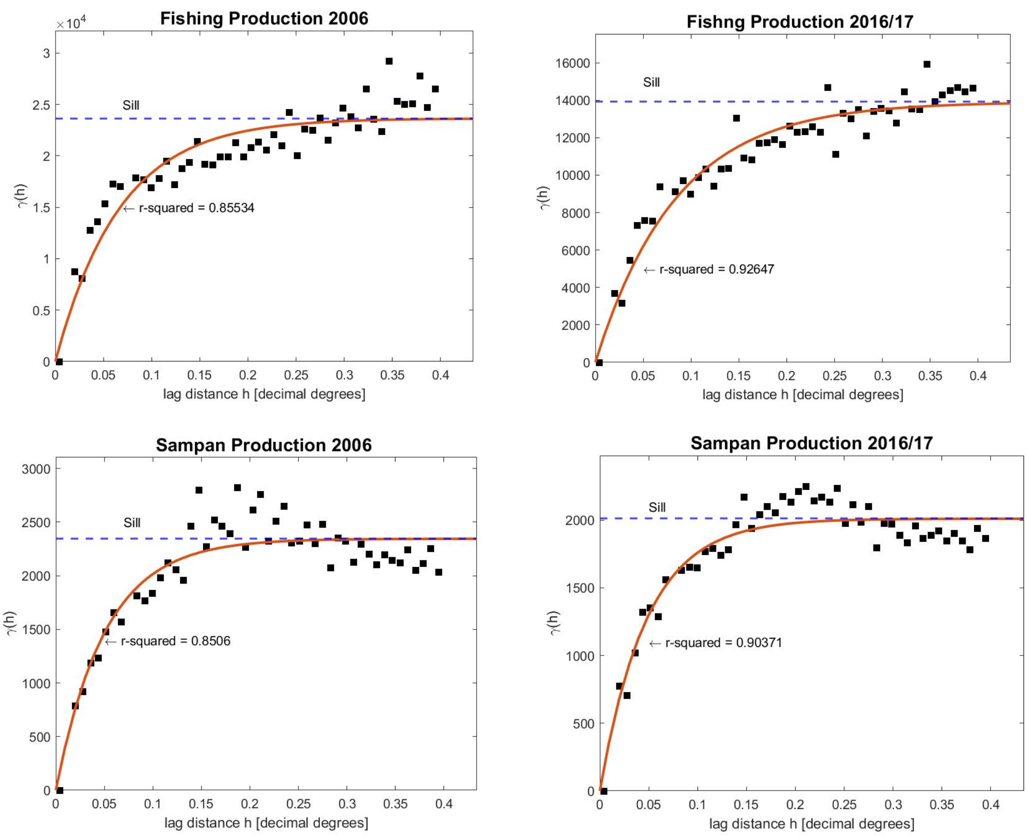

Figure A1. Variogram plots (black squares) with the fitted exponential model (red line) showing convergence to a sill (blue dotted line) and r-squared coefficient of determination values reflecting good fits to the data, corresponding to the maps in Figure 2, for: (top left) all vessels 2006; (top right) all vessels 2016/2017; (bottom left) sampans 2006; (bottom right) sampans 2016/2017. The lag distance *h* is shown in decimal degrees which at the latitude of Hong Kong can be taken to be approximately equidistant for longitude, and hence fixed as a unit of distance, with 0.1 decimal degree ≈ 10 km.

3. Kriging variance (as a measure of map reliability)

The plot of kriging variance shown in Figure A2 below illustrates that interpolation error with these data is dominated by the sampling design of the grid lattice (black dots), so is influenced effectively only through spatial sampling location information, which is fixed and therefore structurally identical for all of the survey data sets. As the spatial autocorrelation with all these data sets is strong, as demonstrated in the variogram plots in Section 3 above, this is the most suitable measure for reporting interpolation error and therefore overall reliability of the estimated map [34]. This map also demonstrates that the lowest kriging variance values, as indicated by blue, lie within the maritime boundary (red line), supporting the greater accuracy of smoothed estimations obtained from those data locations.

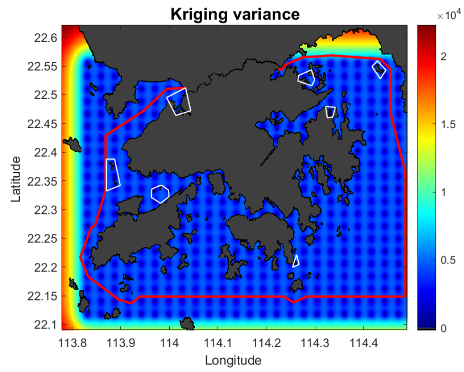

Figure A2. Kriging variance derived for the fish production survey data from all vessels in 2006. The spatial structure is identical for the other 3 data sets due to the fixed sampling design of a 720-hectare grid lattice used throughout. Scale 1:500000.

4. Tables A1 to A4

Estimated fishing production based on the mean range values of 720-hectare quadrats extracted from the HKSAR fishery surveys raw data of 2006 and 2016/2017.

Table A1. All vessels 2006.

Estimated fishing production 2006 (all vessel types)							
Quadrat mean production (kg/ha)	25	75	150	300	500	800	Total
Quadrat mean production (tonnes/quadrat)	18	54	108	216	360	576	-
Number of quadrats fished	100	48	80	57	23	5	313
Total fishing production (tonnes)	1800	2592	8640	12312	8280	2880	36,504

Table A2. All vessels 2016/2017.

Estimated fishing production 2016/2017 (all vessel types)							
Quadrat mean production (kg/ha)	25	75	150	250	350	500	Total
Quadrat mean production (tonnes/quadrat)	18	54	108	180	252	360	-
Number of quadrats fished	83	39	72	78	14	5	291
Total fishing production (tonnes)	1494	2106	7776	14040	3528	1800	30,744

Table A3. Sampans 2006.

Estimated fishing production 2006 (sampans)							
Quadrat mean production (kg/ha)	25	75	150	300	500	800	Total
Quadrat mean production (tonnes/quadrat)	18	54	108	216	360	576	-
Number of quadrats fished	166	58	41	2	0	0	267
Total fishing production (tonnes)	2988	3132	4428	432	0	0	10,980

Table A4. Sampans 2016/2017.

Estimated fishing production 2016/2017 (sampans)							
Quadrat mean production (kg/ha)	25	75	150	250	350	500	Total
Quadrat mean production (tonnes/quadrat)	18	54	108	180	252	360	-
Number of quadrats fished	147	112	37	0	0	0	296
Total fishing production (tonnes)	2646	6048	3996	0	0	0	12,690

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ARTICLE

Research and Experience Reference on London's Response to Climate Change in the Twenty-first Century

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ABSTRACT

London's approaches to tackling climate change after the 21st century are multifaceted and relatively systematic. The aim of this research paper is to analyse London's actions in response to climate change and to draw out what valuable lessons London has for the world in terms of its response to climate change. This paper provides an in-depth analysis of London's policies and actions on climate mitigation in the areas of "greenhouse gas emissions" and "energy infrastructure", and climate adaptation actions in the areas of "city green belt and urban afforestation", "UHI and thermal crisis management" and "water supply infrastructure and sustainable drainage". It then examines the positive aspects of these actions to determine what London has to say about climate change to the rest of the world and other cities. This paper also discovers that to effectively mitigate and adapt to climate change, London has not only established carbon reduction targets, but also created a large academic research network, represented by the LCCP. At the same time, London has developed a scientific climate change adaptation planning framework (P2R2) that focuses on four key areas: Economic, environmental, health, and infrastructure sectors, and three types of risks: Flooding, heat, and water supply, and emphasizes the dynamics and flexibility of each adaptation strategy.

Keywords: Greenhouse gas reduction; Urban green belts; Urban heat island effect; Water supply; Sustainable drainage

1. Introduction

After the turn of the twenty-first century, London has taken several significant studies and actions to combat climate change. On the one hand, mitigation strategies are implemented mainly as "greenhouse

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gas emissions" and "energy infrastructure", such as zero carbon emissions in the building, development industry and energy utility optimisation, and energy monitoring with guidance documents such as the *London Plan 2021*, *Building Regulations*, *London's Plan for 2021*. The other hand is the adaptation to climate change, which includes "urban green belts and afforestation", "thermal crisis management", and "sustainable modifications to water supply and drainage".

With its proactive and multifaceted approach to climate change, London has set an example for cities around the world. Particularly, it has gained a great deal of successful experience in dealing with climate change, particularly in the areas of policy formulation and government planning, climate mitigation and climate adaptation via both mitigation and adaptation strategies. Therefore, the purpose of this paper is to summarise London's successful experience in the previous three areas and to actively assist other cities in addressing climate change issues.

Consequently, the purpose of this paper is to examine the policies and actions that London has developed and implemented in response to climate change, both in terms of mitigation and adaptation, and to analyse and summarise the positive impacts of these policies and actions, as well as the valuable lessons that London can teach the rest of the world about addressing climate change. First, the paper establishes the context for London's response to climate change post-21st century. The paper then discusses mitigation actions in the areas of "greenhouse gas emissions" and "energy infrastructure" as well as adaptation actions in the areas of "green belts and urban afforestation", "UHI and thermal crisis management", and "water supply infrastructure and sustainable drainage". The paper then summarises the positive effects these actions have had on London and the lessons the rest of the world can learn from them. Finally, the paper concludes with conclusions.

2. Background

As a pioneer among developed nations in combating climate change, the United Kingdom was the first nation to respond to the call for sustainable development made at the Rio Global Environment Summit in 1994 with the creation of the country's first "Sustainable Development: Strategic Choices for Britain" to address the escalating issue of climate change [1]. With the 2008 *Climate Change Act*, the United Kingdom became the first nation in the 21st century to legislate medium- and long-term emission reduction targets. The United Kingdom signed the Paris Agreement seven years later. The target is to keep the increase in global average temperature below 1.5 °C above pre-industrial levels (above 1.5 °C, the risk of climate change will threaten humanity's survival) [2]. The United Kingdom has subsequently incorporated temperature increases into its response strategy.

London, as the capital of the United Kingdom in the 21st century, has implemented several policies to address the growing challenges of climate change in terms of carbon emissions, energy demand, waste pollution, and the heat crisis, reorienting the city's economic and environmental sustainability strategies and implementing several actions to combat climate change to achieve these global and national objectives. In 2018, it published *The London Environment Strategy*, the first strategy document for a global city that meets the highest goals of the *Paris Agreement*, which outlines objectives and initiatives in both climate mitigation and climate adaptation (e.g., creating a zero-carbon city) [2]. This paper will therefore focus on the first two aspects of London's response to climate change in terms of its actions and inspirations.

3. Actions to climate change

The section that follows will first describe specific actions and policies for mitigating climate change in London from the perspectives of "greenhouse gas emissions" and "energy infrastructure", and this essay also uses **Figure 1** to show all the mitigation actions and policies to climate change in London. The subsequent section of this article will describe specific actions and policies to adapt to climate change in London from the perspectives of "urban afforestation and city green belts", "UHI and thermal crisis management", and "water supply infrastructure and sustainable drainage", and this essay also use **Figure 2** to show the all the adaptation actions and policies to climate change.

3.1 Mitigation to climate change

Greenhouse Gas Emissions

The UK is the world's eighth largest emitter of carbon dioxide, with London accounting for 8.4% of these emissions [5]. To mitigate climate change, London's first action is to minimise greenhouse gas emissions in the city. In this regard, London has launched a number of climate change mitigation and energy policies and actions, including the *London Plan 2021*, *Mayor's Climate Change Adaptation Strategy Managing risks and increasing resilience*, *Climate Action Strategy 2020-2027*, new *London Declaration*. In 2011, London first set a target of a 60% reduction in emissions by 2025 compared to 1990. In order to achieve this, the *Mayor's Climate Change Adaptation Strategy Managing risks and increasing resilience* plan requires the government (the Mayor) to prepare a climate change mitigation strategy [7]. Under this obligation, the mayor ensured that all future GLA (Greater London Authority) plans and strategies would consider how to reduce carbon emissions. Nine years later, the Climate Action Strategy 2020-2027 identifies specific actions to reduce emissions in London by improving the urban environment [8]. That is, reducing emissions in the public realm by increasing green spaces, urban greenery,

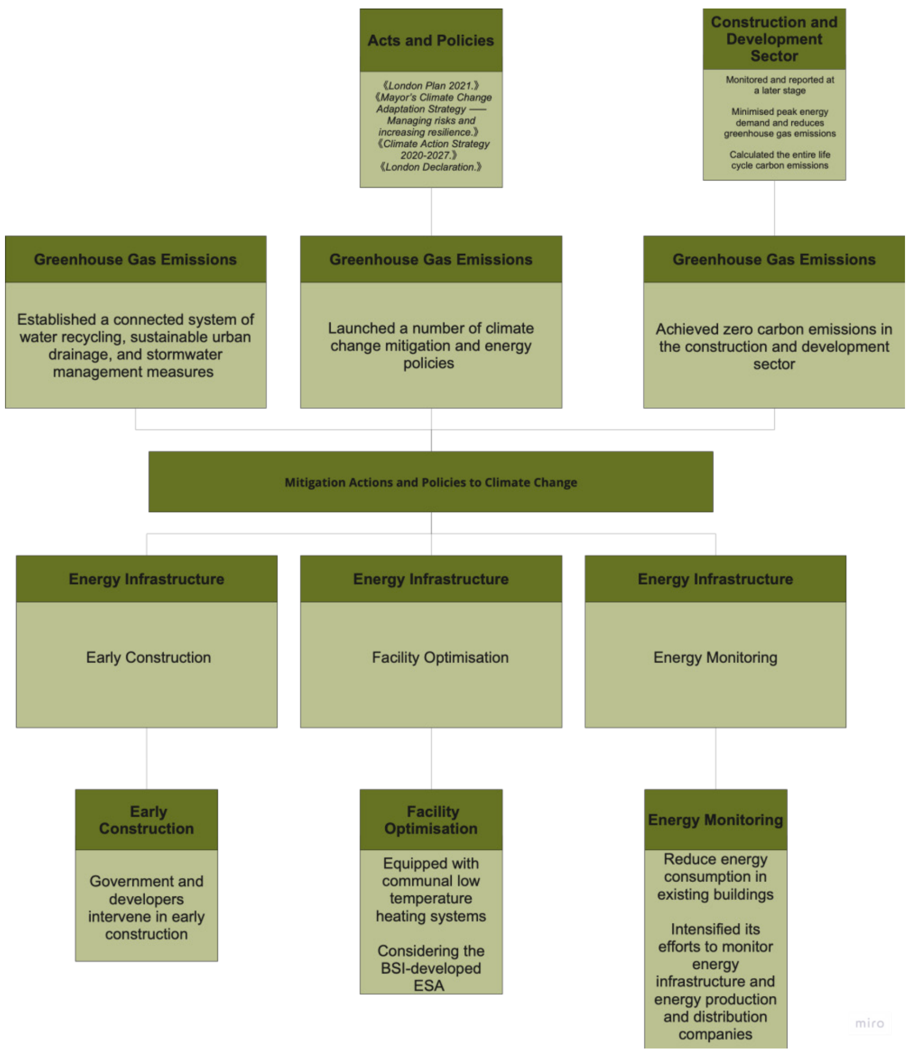


Figure 1. The framework of mitigation actions and policies to climate change.

flood-resistant pavements, adaptive planting systems and heat-resistant materials. At the same time, a connected system of water recycling, sustainable urban drainage, and stormwater management measures to promote greenhouse gas absorption and transformation are being developed through the development of sustainable stormwater and surface water management policies.

London's recent *London Plan 2021* draws on government functions to outline specific actions for the construction and development sector to achieve zero carbon emissions in three areas [4]. Initially, it is proposed that the pre-project operation procedure minimises peak energy demand and reduces greenhouse gas emissions in accordance with various energy hierarchies. Second, the in-situ emission reductions throughout the duration of the project should be at least 35% greater than those mandated by the Building Regulations. Energy efficiency measures should reduce emissions by 10% more than required by the *Building Regulations* for residential development and by 15% more for non-residential development [4]. Plans submitted to the mayor should calculate the entire life cycle carbon emissions using a full life cycle carbon assessment and demonstrate the measures taken to reduce life cycle carbon emissions. Thirdly, energy performance must be monitored and reported at a later stage of the project, such as through the display of energy certificates and online reporting to the mayor for at least five years [20]. The BSI (British Standards Institution) launched the new *London Declaration* in the same year to promote climate-friendly standards as the norm for all industries by publishing practical guidance to assist an increasing number of industries in achieving net-zero emissions. For instance, the BSI and others have developed detailed production standards for the UK battery industry to help the rapidly expanding battery production, recycling, and research sectors of the business collaboration in a manner that reduces emissions and is more sustainable [6].

In recent years, the majority of new developments and construction projects in London have actively contributed to the reduction of CO_2 emissions. In 2016, the construction industry acted. There is a clear hierarchy of energy requirements and CO_2 emissions for all types of buildings, plants, and equipment, as dictated by the *Building Regulations* [4]. In addition, the industry is reducing emissions through the design of energy-efficient sites, buildings, and services. And, where feasible, emissions are reduced further using decentralised energy sources, such as district heating and cooling and CHP (Combined Heat and Power) renewable energy technologies [5].

Energy Infrastructure

Three main areas of climate change mitigation are prioritised in London's energy infrastructure strategies: Early construction, facility optimisation, and energy monitoring. First, the *London Plan 2021* recommends that the government and developers intervene in early construction to anticipate future energy infrastructure requirements and to develop energy master plans for major developments in order to determine the most efficient energy supply options. Simultaneously, major developments within the planned heat network priority areas should be equipped with communal low temperature heating systems, such as zero-emission energy or local secondary heat sources, to mitigate climate change and improve energy supply security [4]. London has responded to the UK Government's energy transition programme by considering the BSI-developed ESA (Energy Smart Appliances) standard for the operation of energy facilities. It is planned to install smart appliances throughout the city to make electricity demand more responsive to the availability of renewable energy. By engaging consumers in the demand management of the electricity system, we can expedite the achievement of net-zero emissions [6].

Thirdly, London has optimised late-stage energy monitoring to, the one hand, reduced energy consumption in existing buildings. On the other hand, climate change has in recent years reduced the demand for heating (natural gas) in winter and increased the demand for cooling (electricity) in summer in the city. As a result, London has intensified its efforts to monitor energy infrastructure and energy production and distribution companies [7] to ensure that their systems are climate-resilient and able to meet seasonal changes in energy demand. New facilities are also required need to be flexible to changes in waste production and resilient to the effects of climate.

3.2 Adaptation to climate change

City green belt and urban afforestation

London views the Green Belt as a climate safety belt to protect its citizens from extreme weather conditions. In recent years, London has adapted to climate change primarily through the Green Belt's provision of carbon sinks and other ecosystem services. Based on the existence of several abandoned sites in the Green Belt that contribute positively to biodiversity, flood prevention, and climate resilience through reuse, specific actions are proposed. And to collaborate with districts and other strategic partners to advance the joint development of ecological services within the Green Belt. Simultaneously, well-managed forested catchment areas can be used to offset the carbon implied and generated by urban areas and to enhance these areas in a manner consistent with the development of London's Green Belt. Second, London developed a specific cross-sectoral Green Belt for climate change adaptation in 2008, implementing adaptation measures while Green Belt and compact city policies gradually restrain urban growth [9]. The Green Belt has acted as a restraint on compact development within cities while easing non-compact planning on the urban periphery. Consequently, with more extreme weather events, London's Green Belt is essential for mitigating climate change, such as rainfall and flooding, as well as reducing heat from the urban heat island effect [10]. Thirdly, London is professionally accountable for Green Belt development by establishing a management company. The City of London Corporation, as the largest manager of the Green Belt, currently oversees more than 35,000 acres of green space. This is equivalent to approximately 5,500 football pitches (removing approximately 16 kt of CO_2 per year, which is 40% of the total emissions of London's boroughs 1 and 2) [8].

Simultaneously, London has improved its urban greenery through the implementation of initiatives

Figure 2. The framework of adaptation actions and policies to climate change.

such as green roofs, landscaping, and building sustainability ratings. Square Mile currently manages approximately 42,600 m^2 of London's green roofs (up from 11,200 m^2 in 2005) and plans to increase this to 65,800 m^2 by 2024. Green roofs absorb approximately 55 percent of the CO_2 emissions from new buildings in zones 1 and 2 of London. Increase the amount of green space and vegetation in London, particularly in Central and East London [7] in terms of landscape beauty. This is because, during warm weather, the prevailing wind is from the east, warming the air as it passes through the city. Keeping East London as green as possible helps to maintain the cooler temperatures in Central and West London. Simultaneously, launch an urban landscaping campaign, including in the east, to identify, prioritise, and implement opportunities to increase green space coverage, and to include the UHI (Urban Heat Island) map in the planning of a London-wide green grid. Thirdly, sustainability is becoming an increasingly important factor when considering the climate adaptation of new buildings, with the majority of buildings being rated for sustainability using BREEAM, the most well-known green rating system in the world. According to recent research by BREEAM creators Knight Frank and BRE, however, London office buildings that meet the most stringent sustainability standards can command rent premiums of up to 12.3% [12]. In recent years, London building developers, represented by the City of London Corporation, have endeavoured to achieve a BREEAM "Excellent" rating for nearly 75% of their new commercial developments (over 20,000 m^2 in terms of floor space) [8]. Additionally, major development applications must contribute to London's urban greenery, including urban greenery as a fundamental element of building and site design. London boroughs have established a UGF (Urban Greening Factor) to determine if new developments contain adequate urban greening.

UHI and Thermal Crisis Management

The heat crisis represented by the UHI has become another major challenge to London's adaptation to climate change in recent years, a phenomenon where urban temperatures are higher relative to surrounding rural areas due to, among other things, urban ground, and anthropogenic heat sources. Compared to the average urban temperature difference of 3-4 °C, central London is up to 11 °C warmer than the surrounding green belt (2003) [7]. In response to the increasing average temperatures in London, the GLA first worked with CIBSE (Chartered Institution of Building Services Engineers) to develop guidelines for developers to address the risk of overheating in buildings [5]. Considering the location of the development in relation to the urban heat island, the guidelines focus on recommending that the adverse effects of UHI should be minimised through the design, layout, positioning, materials, and incorporation of green infrastructure. Examples include installing directional, shading, and high albedo materials; opening windows, insulating, and providing green infrastructure to reduce the amount of heat entering the building; or prioritising the provision of passive and mechanical building ventilation; incorporating cooling hierarchies into the design process to better manage their cooling needs and adapt to climate change and so on [26]. Second of all, in *London Plan 2021*, there are detailed requirements for major building projects to develop an energy strategy that demonstrates that the scheme will reduce the potential threat of excessive internal heating or cooling. For example, reducing the internal heating demand of buildings through designs that increase energy efficiency, reducing heating demand by green infrastructure and new materials, etc. [23].

Meanwhile, London has attempted to encourage boroughs, using its open space strategy, to adapt to climate change by protecting local green infrastructure and the ratio of green space to buildings. UHI is largely caused by the absorption of solar energy by the urban fabric. Meanwhile, the reflectivity of the radiation is mainly determined by physical properties of the buildings and increases the frequency of conditions that lead to heat island creation. The absorptive capacity and share of London's green spaces are therefore even more important. At the same time, the ratio of green space to buildings clearly affects the intensity of the UHI [7]. Referring to model simulations from the Lucid Research Project in London [9], UHI intensity increases as the relative proportion of green space to non-green cover decreases, with each 10% increase in non-green cover increasing UHI intensity by 0.5 degrees Celsius. Removing green space will increase temperatures by 2-3 degrees Celsius. Thirdly, London has in recent years focused on optimising the balance between urban management and the impact of the UHI, the parallel demands of water use and carbon emissions, and thus reducing the negative impact of the UHI. For example, the BRIDGE75 programme, which focuses on central London, aims to provide advice on how and where to maximise the use of government managed to reduce the negative impacts of the UHI, such as increasing the demand for water to maintain vegetation and capturing air pollutants in street canyons [5].

Water Supply Infrastructure and Sustainable Drainage

In relation to London's water needs in recent years, as mentioned above, London has tried to adapt to the changing climate by seeking breakthroughs and progress in water supply and drainage. In terms of water supply, London's main efforts have been to protect and conserve water supplies and to secure demand for use in a sustainable manner. Firstly, Thames Water has in recent years developed a more optimal strategic water supply programme through the water management planning process, including the development of potential new reservoirs, effluent reuse, water transfers and the development of new groundwater sources [11]. The programme should also promote improvements to water supply infrastructure in a timely, efficient, and sustainable manner, considering security of supply and energy consumption. Secondly, to complement the water supply programme and current supply needs, London adopted the *Water Resources Management Plan* in 2019, which retains a large number of the original and efficient water supply infrastructure developments. And the London Government also supports the development of additional water sports centres or related new infrastructure on a pre-existing basis where boroughs have locally identified water supply deficits and where the infrastructure does not have a negative impact on navigation or waterway protection [25]. Thirdly, for new residential developments designed in the city in recent years, London has also set a target of up to 105 liters of mains water consumption per person per day, and to minimise mains water use, building interiors are simultaneously required to protect and conserve water supplies and resources in a sustainable manner [7].

In terms of drainage, London has made sustainable changes mainly based on its own geography and rainfall characteristics. According to the latest Mayor of London statistics, London currently receives more than two feet of rainfall per year. London has therefore first embarked on a win-win city-wide drainage programme for the collection and use of rainwater for non-consumptive purposes, for example using rainwater for part of its domestic use (watering, car washing, etc.) [26]. This reduces the need for water treatment, the pressure on the drainage network (and therefore the risk of flooding), while reducing the volume of diluted wastewater to be pumped to and treated at a sewage treatment plant [7]. Secondly, London seeks to achieve sustainable targets for runoff rates from green spaces and large projects by reducing runoff (e.g., sustainable drainage systems) and storing rainwater (e.g., rainwater harvesting systems). The GLA, Thames Water and the Environment Agency have worked together to identify a "sustainable drainage rating" policy to encourage sustainable drainage. This rating, which initially had a positive impact on large developments, has been applied more recently to smaller sites and infill developments, considering relative cost effectiveness, delivery mechanisms, barriers to implementation, and adaptation pathways [7].

At the same time, London's variable climate means that it is more difficult for local authorities to predict areas at risk of surface water flooding, compounded by London's particular geography, which exposes it to year-round summer convective storms and therefore often has the most unpredictable localised drainage capacity. As a result, London enacted the *Flood and Water Management Act* in 2010, which details how boroughs can establish mechanisms to identify surface water management and develop measures and policies to reduce risk [23]. Meanwhile, for low-lying transport infrastructure (e.g., lower parts of the London Underground network), London's options for managing rainfall runoff include not only the capacity of local drainage systems, but also an additional 12,000 km of roads and footpaths, thus providing an extensive impermeable surface to prevent surface flooding and respond to variable climate change. The aim is to use an optimised drainage network to bring rainfall to the 30-year level.

4. Effect of actions

In the following section, the paper will analyse each of these actions in a relatively positive light, based on the above-mentioned actions of London in terms of mitigation and adaptation, to determine the impact each of these actions has had on London's city and society. This will allow for a clearer understanding of what London's actions in response to climate change over the past few years have taught the world and other densely populated cities.

4.1 Mitigation to climate change

In the face of the climate challenge, London is starting to mitigate climate change by reducing greenhouse gas emissions. Achieving minimal greenhouse gas emissions. This has had a twofold positive effect. On the one hand, London is first reducing emissions from public spaces by increasing urban green spaces, using heat-resistant materials, and developing sustainable drainage systems. This will not only enrich the urban ecosystem and increase urban green space. Priority was also given to addressing sources of air pollution, reducing people's exposure to bad air (children) and improving people's quality of life [25]. On the other hand, by initially requiring the construction and development sector to reduce emissions, London has firstly optimised the process of reducing carbon emissions in the construction sector (pre-project operation, low emission reduction in the middle of the project, and post-project monitoring) and accelerated the transition to low carbon integration in other sectors. Secondly, the process of reducing emissions from construction has significantly strengthened the partnership between government and other partners due to the large number of stakeholders involved in the construction sector [26]. The introduction of documents such as the *Building Regulations* has reinforced the role of mayors and government leadership in climate change. Thirdly, energy efficiency in buildings is being upgraded through energy ratings, low carbon technologies and services, and the energy efficiency of existing and new buildings is being improved, accelerating the city's shift towards a preference for renewable energy. Fourthly, the combination and use of district heating and cooling, CHP and renewable energy technologies optimises the approach to new and viable building and development strategies and upgrades the model for future sustainable urban development.

Meanwhile, the energy infrastructure strategy has had three main positive effects. Firstly, the early construction and intervention of London's infrastructure identify the most efficient energy supply, while efficiently producing energy to meet the city's needs and avoiding energy shortages due to the rapid urban growth of the population. Secondly, the optimisation and transformation of facilities such as the communal low temperature heating system and ESA standards have brought security and reliability of supply to London's energy. The optimisation process specifically involves forecasting the heat and power infrastructure, modifying the built environment to reduce demand, and transporting electricity [24]. Demand shifting and storage options that consider "smart" energy offer significant potential for future energy reserves. And optimising and developing low carbon and decentralised energy supplies. For example, the development of combined cooling, heat and power systems, small-scale renewable energy installations (wind and solar), etc. within the City of London, replacing some of the electricity supplied by the national grid and significantly reducing losses due to long-distance transmission [13]. Combined with the previously mentioned reduction in greenhouse gas emissions, London's low carbon energy consumption collectively makes a significant contribution to climate change mitigation [21]. Thirdly, late-stage energy monitoring increases the affordability and cost competitiveness of energy. Referring to the arguments of representatives from the electricity and development sectors, London's gas and electricity costs are more competitive, and reserves are more abundant through stronger links with the building sector and energy production and distribution companies [16].

4.2 Adaptation to climate change

The Green Belt brings a wide range of environmental benefits to London's periphery and plays an important role in London's adaptation to climate change. First, the ecosystem services of the Green Belt strengthen the link between renewable resources and nature around the city. These green spaces are reconceptualized as areas that provide a variety of functions of strategic importance for climate adaptation, river management, and management of biodiversity [10]. For example, green belts provide habitat for wildlife around London and provide more opportunities for people to travel and enjoy open land and countryside outside the city. In particular, it provides more land for agriculture to grow to produce healthy seasonal food [16], and a more sustainable and healthier growing environment also drives the local rural economy and employment development. Second, the actions of the Green Belt in managing rainfall and flooding provide multiple ecosystem benefits to different types of open space around London, including urban cooling, improved air quality, flood protection and carbon sequestration (especially in woodland areas), and local food production [15]. In recent years, non-compact planning has similarly evacuated inner-city London from residential and demographic pressures. In addition, the creation of a dedicated Green Belt authority has played a crucial role in absorbing carbon emissions around London, reducing waste and supporting the circular economy. In recent years, documents such as the *London Plan 2021* have also set out action targets for the simultaneous development of a circular economy, calling for a meeting or exceeding London's target of recycling 65% of its waste by 2030 [23]. As a result, thousands of acres of the green belt can absorb huge amounts of carbon dioxide and waste each year and dispose of it naturally through land decomposition, green plants, etc. Such treatment substantially reduces the potential variation in the amount of waste within the city, significantly shortens the process and time from waste collection to treatment and final disposal, and simultaneously promotes the development of an internal and external urban cycle and circular economy [7].

In terms of urban greening, the actions undertaken in London to adapt to the climate have brought similarly positive results. First, the construction and centralized management of green roofs have alleviated the pressure of water stress in London. This is since green living roofs that do not require irrigation have the potential to mitigate the impact of runoff and storm events, thereby reducing negative downstream impacts on drainage infrastructure. Similarly, source control techniques for stormwater management through an integrated approach to active roofs can effectively reduce flood risk by avoiding the increased surface and sewer flooding and flood risk associated with frequent rainfall in London [26]. At the same time, green performance can reduce the absorption of nighttime radiation from buildings and roofs, thus allowing buildings with green roofs to reduce temperatures and the urban heat island effect and receive wider environmental benefits [17].

Secondly, landscaping increases the importance of landscape planning and development perceptions in London, and more importantly, London's environmental quality through appropriate green infrastructure in the landscape. Green landscapes on the one hand can reduce the negative impact of UHI, absorb harmful and greenhouse gases, and reduce air pollution. On the other hand, it can also serve and enhance the cultural identity of London's urban and suburban areas together through the maintenance of the uniqueness of the London landscape, for example, by promoting community health and well-being through community gardening [18]. Thirdly, the sustainability rating of buildings on the one hand safeguards the well-being of residents, and the BREEAM assessment covers all aspects of residents' livelihood and well-being from energy, land use, materials, management, pollution, transport, waste, innovative water, health, etc. On the other hand, it also drives the economic vitality of the London development market, driving a positive cycle of economic benefits by giving the project a sustainability edge.

At the same time, in reducing the negative impact of the UHI, London has first acted on materials, major construction projects, etc. from a construction perspective. This has resulted in a significant reduction in building temperatures and avoided air pollutants from the constant high temperatures in buildings, as well as reducing the incidence of heat stroke and heat cramps, heat-related mortality, respiratory problems, and other human health problems in buildings. At the same time, the reduction in building temperatures simultaneously reduces the electricity demand for air conditioning (especially in summer) and avoids urban overload due to excessive electricity use [24]. As well, power plants increase the production of energy from fossil fuels by providing the additional energy required, thus increasing greenhouse gas emissions and air pollutants, including carbon monoxide (CO), carbon dioxide (CO_2), sulfur dioxide (SO_2), nitrogen oxides (NO_x), particulate matter, and mercury (Hg) [19]. And it also slows down global warming and climate change a result. Second, London's use of green infrastructure to absorb temperature and solar energy, on the one hand, substantially increases the ecological benefits of the city; greenery is an excellent insulator in summer, reducing the overall urban heat island effect, and cooling the surrounding environment, further reducing the need for air conditioning from the side. At the same time, with the coverage of green facilities, a large number of plants (open-air planting, street trees and curb planting) are able to absorb CO_2 and produce fresh air, and air quality is improved [25]. On the other hand, the improvement cost of plants is relatively low. Thus, similar practices not only produce cooling effects in urban areas, but also reduce cooling costs. Third, after the London government optimized the management of the UHI, the temperature in the city center continues to decrease through water, the global leader in carbon emissions in a parallel way. This has served as a positive model for other very densely populated central cities.

Fourth, concerted efforts in drainage and water supply have also made London more resilient to climate change in recent years. First, the optimization of water supply and drainage facilities by companies and institutions such as Thames Water protects and improves the environment while securing the investments needed for public water supply and drainage in the region [14], providing London with safe and sustainable water resources. Second, London's water resources are further scarce at a time of dramatic climate change. However, London has introduced a series of policies and bills detailing per capita water consumption, surface water management rules, and other detailed requirements, each of which is more precise and reasonable, and this has truly reduced London's growing water demand and safeguarded residential water sanitation and health. Thirdly, the *Flood and Water Management Act* and other documents that London has introduced in response to its own geography have strongly supported London to better cope with floods, droughts, and extreme heat, providing advice and warnings during extreme heat, cold and flood events, helped and protected Londoners by planning systems to make new developments more efficient in terms of water use and to provide reasonable control of temperature rise and flood risk.

5. Experience reference and discussion

Climate change has become a common challenge for humankind. To cope with climate change, both mitigation and adaptation are needed, and while significantly reducing greenhouse gas emissions, proactive adaptation actions are needed to mitigate the adverse impacts of climate change on natural ecosystems and socio-economic systems [24]. To actively respond to global climate change, London has accumulated a lot of experience in three major areas, including policy formulation and government planning, climate mitigation, and climate adaptation, which have some valuable insights for other cities in the world to respond in the future. In **Figure 3**, this essay uses the graph to show the summary of experience reference on London's response to climate change.

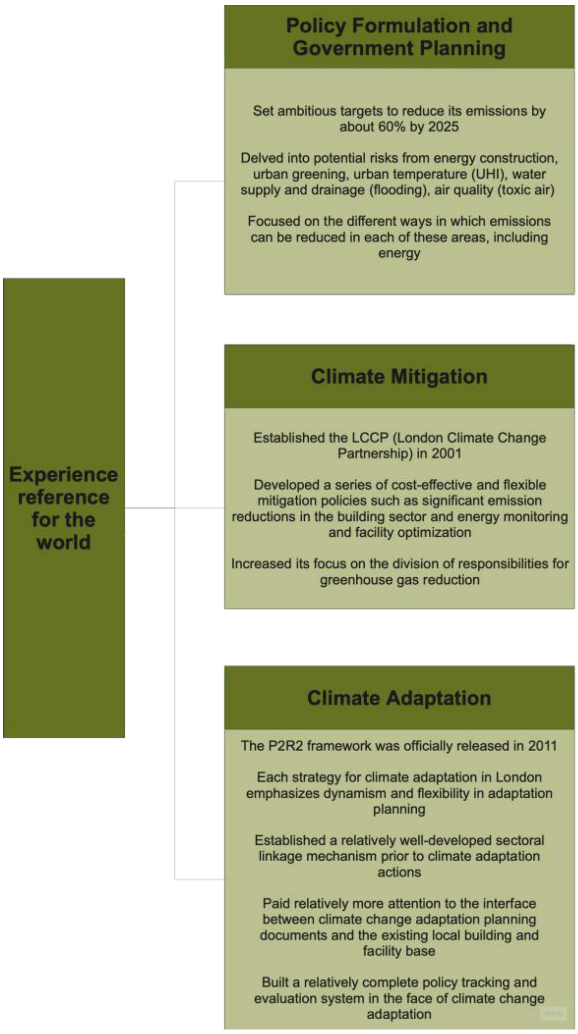


Figure 3. The summary of experience reference on London's response to climate change for the world.

Since 2005, London has developed and implemented policies, targets, and plans to address climate change. Firstly, in terms of low carbon emission reduction, London has set ambitious targets to reduce its emissions by about 60% by 2025 compared to 1990 (19.6 million tons of CO_2 emissions per year) and to achieve zero emissions by 2030. However, the UK's sixth Carbon Budget will incorporate the UK's share of international aviation and shipping emissions for the first time which means it has already achieved the 60% reduction target to some extent [27]. Second, London delves into potential risks from energy construction, urban greening, urban temperature (UHI), water supply and drainage (flooding), air quality (toxic air), and many other aspects to ensure that the city supports low-income people from the cost, and that residents benefit from warmer, energy-efficient homes, cleaner air, and new green jobs from faster action. Third, London looks at the different ways in which emissions can be reduced in each of these areas, including energy [4]. On the one hand, the government is progressively strengthening planning leadership and funding to meet emissions reduction targets and advancing infrastructure planning for energy, green, and drainage hearings. On the other hand, the government has planned and promoted the growth of other aspects of society through the concept of sustainable development and the means to address climate change, based on achieving the net zero target [21]. This includes supporting tens of thousands of jobs, improving health through better air quality and more active lifestyles, reducing inequality, and improving the well-being and quality of life of residents.

London has made great efforts and sacrifices in climate mitigation. First, to effectively mitigate climate change, the Greater London Council established the LCCP (London Climate Change Partnership) in 2001, with a core membership of representatives from over 30 organisations including the council, planning, finance, health, environmental management, climate research, and the media. The partnership has established an extensive network of academic research and information communication through projects and forums and has involved over 200 organizations. Second, London has developed a series of cost-effective and flexible mitigation policies [22] that have led to the active implementation of emission reduction targets in all sectors and all regions of the UK, such as significant emission reductions in the building sector and energy monitoring and facility optimization. These policies and measures will secure and strengthen the UK's national competitiveness while ensuring that industry and commerce are served at lower energy costs and alleviating energy fuel poverty, improving air quality in urban areas, reducing adverse health risks, and expanding exports and developing new business opportunities. Third, in terms of greenhouse gas reduction, London has increased its focus on the division of responsibilities for mitigation actions. On the government side, the importance of climate mitigation actions is highlighted through bills and policies, such as the 2008 *Climate Change Act*, the 2020 *Climate Emergency Action Plan* [21] and so on, which clarify the legal obligations of cabinet ministers. In terms of social division of labor, London has adopted the *Building Regulations*, *London Declaration* and other documents that focus on the primary responsibility of the building industry to reduce emissions and set various levels of standards for the building industry. A climate mitigation partnership has been established and promoted to promote the adoption of mitigation measures and to empower key stakeholders (development and construction of major construction and energy projects) to take proactive measures to reduce greenhouse gas emissions and reduce reliance on fossil fuels.

At the same time, London is more representative of climate change adaptation, and its planning proposals for adaptation are considered to be at the forefront of global adaptation action. For a long time, climate change strategies around the world have centered on mitigation, with adaptation policies and actions lagging far behind the process of mitigation. Given the difficulty of mitigating the impacts of climate change in the short term, London has a higher urgency to develop and implement climate change adaptation policies and increase resilience to the adverse impacts of climate change. This has enabled the establishment of a more developed institutional system for climate change adaptation [3]. First, the P2R2 framework, which was officially released in 2011, divides climate change adaptation actions into four levels: Prevent, prepare, respond, and recover. Scientific climate change adaptation plans, action plans, and other planning-type documents, such as the *Draft London Climate Change Adaptation Strategy*, are developed in the initial planning stage [11]. Thus, London can systematically assess the impacts of climate change on London and develop more comprehensive and detailed adaptation actions. Second, each strategy for climate adaptation in London emphasizes dynamism and flexibility in adaptation planning, highlighting future climate change and uncertainty issues in London's development process. For example, London focuses on three categories of climate risks, namely flooding, heat and water supply. Based on the systematic assessment of the first three types of risks, the adaptation strategy proposes specific action plans for each of the four key areas most affected by climate change, the economy, environment, health, and infrastructure [26], and sets up a policy tracking and evaluation mechanism to track and detect the progress and effectiveness of adaptation efforts in a timely manner.

Third, London has established a relatively well-developed sectoral linkage mechanism prior to climate adaptation actions. Within the government, adaptation to climate change requires the establishment of cross-regional and cross-departmental coordination bodies to achieve effective policy communication. For example, the Green Belt, drainage, and water supply sectors all require consistent policy regulation in response to London's floods. Establishing effective communication channels between the government and other stakeholders is a key success factor for adaptation in London, and communication between stakeholders helps to develop scientific adaptation planning and helps to stimulate the participation of all parties [11]. Fourthly, London has paid relatively more attention to the interface between climate change adaptation planning documents and the existing local building and facility base, for example, the reduction of UHI process, most buildings are rated using the new BREEAM thus making sustainability an increasingly important factor for local London office and retail spaces, promoting a shift in London's governance model from emergency management to risk management. Finally, London has built a relatively complete policy tracking and evaluation system in the face of climate change adaptation. Policy tracking and evaluation help to keep track of the progress and effectiveness of climate change adaptation efforts and plays an important role in promoting the implementation of relevant policies by various stakeholders [25]. For example, the Sustainable Drainage Rating developed by the GLA, Thames Water and the Environment Agency has been instrumental in optimizing London's drainage system and saving water. In addition, the results of policy tracking and evaluation can help guide adaptation planning in line with the current state of adaptation in London, resulting in long-term dynamic adaptation planning [26]. Adaptation to climate change could consider introducing third-party assessments to provide an objective evaluation of policy implementation and goal achievement.

6. Conclusions

After the 21st century, London, has played a leading role in addressing climate change. This paper discusses the actions taken by London in recent years and the positive effects on urban development from the perspectives of climate mitigation and adaptation. London has gained extensive experience in three key areas: Policy and government planning, climate mitigation, and adaptation for other cities worldwide. First, London has set ambitious carbon emission reduction goals. Simultaneously, London has considered and investigated the potential risks in numerous ways, including energy production from a human perspective. In addition, London has investigated various methods for reducing emissions in each sector, including the application of sustainable development principles and methods for combating climate change. Second, to effectively mitigate climate change, London has established a vast academic research network, represented by the LCCP, which provides crucial support for scientific decision-making. In the meantime, London has developed several flexible and cost-effective mitigation policies, including substantial emission reductions in the building sector. In addition, London has paid more attention to the allocation of responsibilities for mitigation actions in terms of greenhouse gas reduction.

Thirdly, London is better represented in terms of climate change adaptation. First, London has developed a scientific planning framework for climate change adaptation (P2R2) that focuses on four key areas: Economic, environmental, health, and infrastructure sectors, as well as three types of risks: Flood, heat, and water supply, with an emphasis on the dynamic and flexible nature of each adaptation strategy. London has established a relatively well-developed sectoral linkage mechanism and a relatively comprehensive policy tracking and evaluation system established. In addition, London has given greater consideration to the interface between climate change adaptation planning documents and the existing local building and facility base. Addressing climate change provides a socio-economically inclusive and environmentally friendly sustainable development for the city, which necessitates the future collaboration of government, society, business, and community stakeholders.

Conflict of Interest

There is no conflict of interest.

References

[1] Farand, C., 2019. Britain's Bid to be Climate World Leader [Internet] [cited 2023 Feb 24]. Available from: https://theecologist.org/2019/jan/30/britains-bid-be-climate-world-leader.

[2] UNFCCC, 2022. The Paris Agreement [Internet]. Available from: https://unfccc.int/process-and-meetings/the-paris-agreement.

[3] Zhao, X., Qi, Y., Li, J., 2021. International best practices of climate change risk assessment system and their implications for China. Environmental Protection. 49(8), 39.

[4] Fischer, A., 2021. How Energy Efficiency will Power Net-Zero Climate Goals—Analysis [Internet]. Available from: https://www.iea.org/

commentaries/how-energy-efficiency-will-power-net-zero-climate-goals.

[5] Mayor of London, 2016. London's Response to Climate Change [Internet]. Available from: https://www.london.gov.uk/sites/default/files/the_london_plan_malp_march_2016_-_chapter_5_-_londons_response_to_climate_change.pdf.

[6] BSI, 2021. International Commitment Pledges to Accelerate Transition to Net Zero [Internet] [cited 2022 Nov 20]. Available from: https://www.bsigroup.com/en-GB/about-bsi/media-centre/press-releases/2021/september/international-commitment-pledges-to-accelerate-transition-to-net-zero/.

[7] BURNS & NICE Ltd, London, 2011. Managing Risks and Increasing Resilience [Internet]. Available from: https://www.london.gov.uk/sites/default/files/gla_migrate_files_destination/Adaptation-oct11.pdf.

[8] City of London, 2020. Climate Action Strategy 2020-2027 [Internet] [cited 2022 Nov 2]. Available from: https://www.cityoflondon.gov.uk/assets/Services-Environment/climate-action-strategy-2020-2027-20-10-20.pdf.

[9] Mees, H.L.P., Driessen, P.P., 2011. Adaptation to climate change in urban areas: Climate-greening London, Rotterdam, and Toronto. Climate Law. 2(2), 251-280.

[10] Amati, M., Taylor, L., 2010. From green belts to green infrastructure. Planning Practice & Research. 25(2), 143-155.

[11] BICP Intelligence Unit, 2019. Draft London Climate Change Adaptation Strategy [Internet]. Available from: http://www.bjcsghxh.com/data/file/5e8948332ce221c5613285a3.pdf.

[12] James, B., 2021. Designers, Manufacturers and Installers of Shading, Screening, and Acoustic Solutions [Internet] [cited 2022 Nov 22]. Available from: https://waverley-co-uk.translate.goog/green-london-office-buildings-could-achieve-12-3-rental-premium/?_x_tr_sl=en&_x_tr_tl=zh-CN&_x_tr_hl=zh-CN&_x_tr_pto=sc.

[13] Mayor of London, 2018. London Environment Strategy Executive Summary [Internet] [cited 2022 Nov 7]. Available from: https://www.london.gov.uk/sites/default/files/osd21_es_executive_summary.pdf.

[14] Water Resources East, 2022. An Introduction to Water Resource Management Planning [Internet] [cited 2022 Nov 1]. Available from: https://www.anglianwater.co.uk/siteassets/household/about-us/wrmp-an-introduction.pdf.

[15] London Green Belt Council, 2016. The Benefits of London's Green Belt [Internet] [cited 2022 Nov 12]. Available from: https://londongreenbeltcouncil.org.uk/wp-content/uploads/2016/05/LGBC-leaflet.pdf.

[16] Mayor of London, 2018. Helping London's Green Belt farms to Prosper [Internet] [cited 2022 Nov 23]. Available from: https://www.london.gov.uk/programmes-and-strategies/environment-and-climate-change/environment-publications/helping-londons-green-belt-farms-prosper.

[17] Greater London Authority, 2008. Living Roofs and Walls—Technical Report: Supporting London Plan Policy [Internet]. Available from: https://www.london.gov.uk/sites/default/files/living-roofs.pdf.

[18] Pochee, H., Johnston, I., 2017. Understanding design scales for a range of potential green infrastructure benefits in a London Garden City. Building Services Engineering Research and Technology. 38(6), 728-756. doi: 10.1177/0143624417734526.

[19] Rinkesh, 2016. Effects and Solutions to Urban Heat Island [Internet]. Available from: https://www.conserve-energy-future.com/effects-solutions-urban-heat-island.php.

[20] Ministry of Housing, Communities & Local Government, 2015. A guide to Display Energy Certificates and Advisory Reports for Public Buildings [Internet]. Available from: https://www.gov.uk/government/publications/display-energy-certificates-and-advisory-reports-for-public-buildings/a-guide-to-display-energy-certificates-and-advisory-re-

ports-for-public-buildings.

[21] London Canada, 2022. Climate Emergency Action Plan [Internet]. Getinvolved. London. [cited 2022 Oct 4]. Available from: https://getinvolved.london.ca/climate.

[22] UK Climate Change Committee, 2008. UK Committee on Climate Change Insight Report (I) UK Climate Change Bill [Internet] [cited 2022 Oct 6]. Available from: https://www.theccc.org.uk/wp-content/uploads/2020/10/CCC-Insights-Briefing-1_CN.pdf.

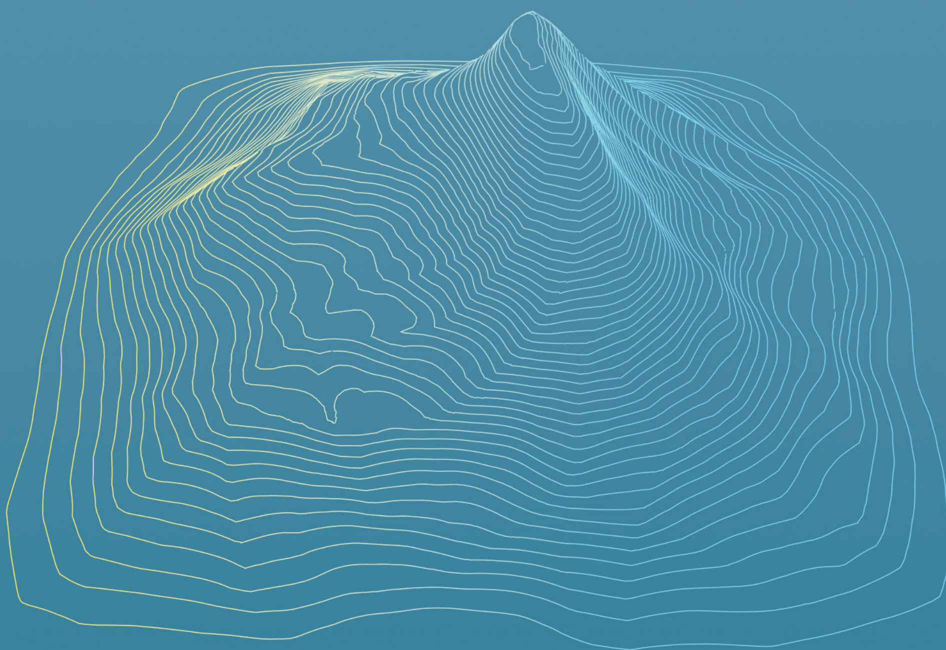
[23] Mayor of London, 2021. The London Plan 2021 [Internet]. [cited 2022 Oct 24]. Available from: https://www.london.gov.uk/programmes-strategies/planning/london-plan/new-london-plan/london-plan-2021.

[24] Kolokotroni, M., Ren, X., Davies, M., et al., 2012. London's urban heat island: Impact on current and future energy consumption in office buildings. Energy and Buildings. 47, 302-311.

[25] Ministry of Housing, Communities & Local Government, 2021. National Planning Policy Framework [Internet]. Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1005759/NPPF_July_2021.pdf.

[26] HM Government, 2022. UK Climate Change Risk Assessment 2022 [Internet]. Available from: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1047003/climate-change-risk-assessment-2022.pdf.

[27] Department for Business, Energy & Industrial Strategy, 2021. UK Enshrines New Target in Law to Slash Emissions by 78% by 2035 [Internet]. Available from: https://www.gov.uk/government/news/uk-enshrines-new-target-in-law-to-slash-emissions-by-78-by-2035.



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