Unlocking the Potential of Earth Observation Data in Cultivating a Climate-Resilient City

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Key words: Earth Observation; Remote Sensing; Satellite Image; LiDAR; UAV; Aerial Image; Climate Resilience, Climate Adaptation

SUMMARY

In October 2021, the Government of the Hong Kong Special Administrative Region published the "Hong Kong's Climate Action Plan 2050" to build upon the previous "Hong Kong's Climate Action Plan 2030+". One of the key strategies of this new plan outlines the measures of climate change adaptation and resilience, with the aim of protecting the lives, health, and property of the people from extreme weather events, as well as strengthening the overall resilience of the community in Hong Kong.

The adaptation strategy focuses on solutions to combat extreme disasters and weather events, while also safeguarding the water supply. The resilience strategy, on the other hand, concentrates on preparedness to more extreme disasters and enhancing capabilities in post-disaster recovery.

Earth Observation (EO) data can play a crucial role in implementing these strategies in both monitoring and evaluation. Through structural collection of EO data, well-defined methodologies, application of comprehensive spatial tools and GeoAI algorithms, and spatial presentation capabilities, EO data can be leveraged to provide recommendations to policymakers in understanding the effectiveness of policies and making more informed decisions related to climate change adaptation and resilience. It also highlights the pivotal involvement of Hong Kong's land surveyors in contributing to the achievement of the United Nations' Sustainable Development Goals (SDGs) through their work in this domain.

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1. WEATHER RELATED THREATS

According to the World Meteorological Organization's preliminary assessment, 2023 is likely to be the warmest year on record (WMO, 2024). Global mean sea level continued to rise, reaching a new record high in 2023 (Johnson et al., 2024). The Sixth Assessment Report from the Intergovernmental Panel on Climate Change (IPCC) confirms that human-induced climate change is unequivocal, with global temperatures 1.1°C higher than pre-industrial levels. The report addressed the scientific study on climate change, which is already affecting every inhabited region across the globe, with human influence contributing to many observed changes in weather and climate extremes (IPCC, 2021).

Like other coastal cities, Hong Kong is prone to the impacts of climate change. The mean sea level in Victoria Harbour went up at an average of 31 mm per decade from 1954 to 2020 (HKO, 2024). With all twelve months warmer than usual, 2023 was one of the second warmest years on record, with the annual mean temperature reaching 24.5 degrees, 1.0 degree above the 1991-2020 normal (HKO, 2024). Over the past century, the number of very hot days in Hong Kong increased from 2.2 to 21.7 days, and the number of hot nights increased from 0.7 to 27.3 days. Every year, around 16 tropical cyclones occur inside Hong Kong's area of responsibility, which pose different levels of threat to Hong Kong (HKO, 2024). For instance, the passage of Super Typhoon Mangkhut in 2018 caused at least 458 injuries. There were more than 60,000 reports of fallen trees, the highest number on record (HKO, 2020).

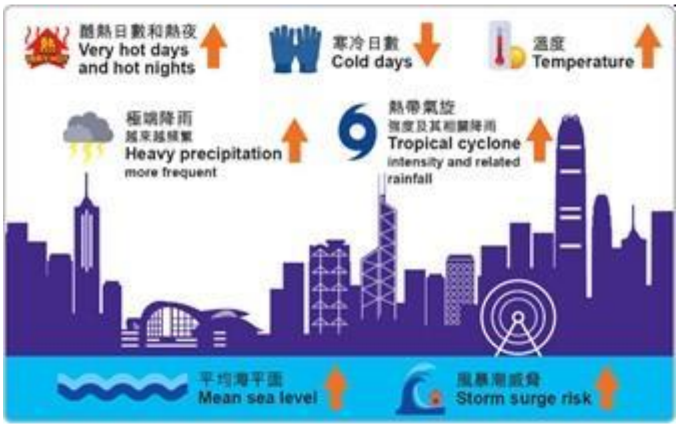

Figure 1 - Climate Change in Hong Kong (HKSAR Government, 2024)

2. RESPOND TO THREAT

The inter-departmental Steering Committee on Climate Change and Carbon Neutrality, chaired by the Chief Executive, was established in July 2021 to formulate the overall intergovernmental strategy and oversee the coordination of various actions (HKSAR Government, 2021). The Government of the Hong Kong Special Administrative Region then published the "Hong Kong's Climate Action Plan 2050" to build upon the previous "Hong Kong's Climate Action Plan 2030+" after three months (HKSAR Government, 2021). One of the key strategies of this new plan outlines the measures of climate change adaptation and resilience to protect the lives, health, and property of the people from natural hazards and strengthen the overall resilience of the community in Hong Kong (EB, 2021).

To oversee the effective implementation of all these actions, the Environment and Ecology Bureau (Previously named the Environment Bureau) set up the Office of Climate Change and Carbon Neutrality, led by the new Commissioner for Climate Change to strengthen coordination among government departments on the strategies, policies, and action plans in combating climate change (HKSAR Government, 2021). In addition, the Council for Carbon Neutrality and Sustainable Development, a dedicated advisory council from widespread public stakeholders, was formed in May 2023 to offer advice to the Government and promote public awareness and understanding of climate change (HKSAR Government, 2023).

Considering the accumulation of experience in combating natural hazards, including tropical cyclones, rainstorms, and sea level rise, Hong Kong has laid a solid foundation for strengthening the design of buildings and infrastructure facilities, and enhancing drainage management and landslip preventive measures. Resilience focuses on preparing for emergencies by raising community awareness, preparing contingency plans for natural disasters and transport systems, and improving warning and monitoring systems (HKSAR Government, 2021).

3. EARTH OBSERVATION INDUSTRY

According to the EU Agency for the Space Programme (2024), Earth Observation (EO) is the process of gathering information about the Earth's surface, waters, and atmosphere via ground-based, airborne and satellite remote sensing platforms. The United Nations General Assembly Resolution 41/65 of 1986 addressed the principles of remote sensing and reflected the best practices of spacefaring nations, which the activity means the operation of remote sensing space systems, primary data collection and storage stations, and activities in processing, interpreting, and disseminating the processed data. (United Nations General Assembly, 1986). The advancement of technology, the initiative of commercializing space (US Government, 2015) (European Commission, 2016), and the adoption of an open data policy of satellite imagery data (Irons et al., 2012; European Commission, 2014) empowered the rapid growth of all sectors of the EO industry. Generally, the EO industry can be categorized into a pipeline from (i) data collection, and (ii) data processing to (iii) services and applications from spaceborne and airborne data, supplemented by in-situ ground truth data.

The data collection sector is considered the upstream component in the EO industry, collecting petabytes of data about our planet daily from various sensors. Public and private entities worldwide are launching diverse sensors on satellite constellations into the polar or geostationary orbit, either for regular data capture missions or on-demand tasking. Active sensors emit energy, capturing reflected light across various wavelengths, while passive sensors detect naturally occurring light, capturing a broad spectrum of electromagnetic waves. The captured data is then directly transmitted to ground segment infrastructure for further use. Additionally, following defined flight plans, sensors mounted on aircraft and helicopters are commonly deployed to collect territory-wide data. Lightweight sensors on unmanned aerial vehicles have also become favorable for collecting EO data in smaller regions.

The data collected from spaceborne and airborne sensors is named primary data (UNGA, 1986). The data processing sector conducts various preprocessing operations on this primary data, such as atmospheric, radiometric, and geometric corrections (Frazier et al., 2021). These preprocessing steps generate different types of processed data (UNGA, 1986), or named derived data, with each level of processing derived to the needs of the end-users. For example, some companies offer Analysis Ready Data (ARD), a finalized level of processing that includes all necessary preprocessing steps, mosaicking, tiling, seamline editing and color enhancement from multiple sources, before delivering the data to users. Users can then access or download the ARD product directly for their own application. Additionally, many public and private organizations have developed cloud-based platforms with well-defined catalogs to facilitate easy searching, fast streaming, and downloading of large data sets. These platforms also provide on-the-fly data processing functions (Microsoft, 2024; EODH, 2024; ESRI, 2024). For example, the Copernicus program from the EU employs a multi-pronged approach for the public to access Sentinel Reference Products and Copernicus Services Reference Products such as Copernicus Open Access Hub, the Collaborative Data Platform, as well as the individual Copernicus service-specific web portals (Copernicus, 2024).

The advancements in artificial intelligence and cloud computing enable service providers in the service and application sector to integrate EO data with other relevant spatial data sources to develop a wide range of applications across multiple domains. Combining with various geospatial datasets, EO data is not only used to create detailed and up-to-date maps that can aid in land management, urban planning, and infrastructure development (Kakiuchi, 2002; Cantou, 2018; IGN FI, 2024), but also applies in the environmental domain. The integration of EO data with ground-based sensors and socioeconomic information has enabled the development of applications for monitoring environmental and meteorological parameters, assessing climate change impacts. The integration of EO data has also proven valuable in the social and governance domain, where it is used to track and report on sustainability metrics, monitor human settlements, and support urban planning and management decisions (Mihir et al., 2020). As demonstrated in the study by Dang et al. (2022), precise agriculture is another area where the fusion of EO data with AI analytics has revolutionized precision farming practices, optimizing resource use and improving crop yields. These applications have been instrumental in supporting policymakers and decision-makers with data-driven insights.

As technological advancements continue to unfold, the future holds the promise of even lighter and smaller EO payloads (Kääb et al., 2021). Satellite and aircraft-mounted instruments capable of millimeter-grade resolution (Smith et al., 2020), hyperspectral imaging (Marinelli et al., 2019), and multi-return LiDAR (Wang et al., 2021) will soon be available, enabling the collection of precise and accurate information about our planet. Alongside these hardware improvements, the maturation of edge computing and other data processing techniques accelerate the transformation of primary data into ARD products (Guo et al., 2020) in 3D-oriented (Maxar, 2022) and real-time. These products can create more applications that analyze complex issues and develop solutions to address the intricate challenges facing by our world. The ability to continuously monitor and understand the human footprint on the planet is crucial, and EO data is emerging as a vital tool in this endeavor.

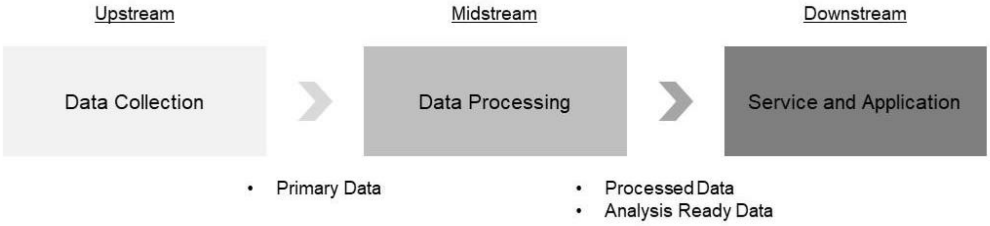

Figure 2 - The Categorization of EO Industry

4. EO APPLICATION IN CLIMATE ADAPTATION AND RESILIENCE

4.1 Quick Response and Recovery

When severe natural hazards affect Hong Kong, an alert message needs to be quickly disseminated to the public, and the Government must respond quickly to allow the community to return to their normal daily activities at the earliest opportunity. The Government's interdepartmental steering committee coordinates government departments and supervises the various stages of preparedness, contingency, and recovery, as well as setting priorities for different response tasks, so that various government departments can take prompt action under their domain. In this regard, accurate information sharing becomes essential.

4.1.1 Share Additional Data in Emergencies

To support the real-time sharing of emergency information brought by natural hazards among relevant government departments, government departments such as Geotechnical Engineering Office (GEO) of the Civil Engineering and Development Department (CEDD) makes use of Common Operational Picture (COP) in an Emergency Monitoring and Support Centre (EMSC) to display and monitor the city's situation in real-time, facilitating the formulation of contingency plans and measures (HKSAR Government, 2020). The sharing of EO data, such as satellite orthomosaic and aircraft orthomosaic can provide a comprehensive and up-to-date scene of the territory, allowing the real-time identification of the extent of the affected area and its respective land cover type present, which then facilitates a regional basis damage assessment and the allocation of its resources in response to the disaster, and to prioritize the most severely affected area in need of immediate attention. By sharing consistent information and the latest status, different government departments in the COP that are responsible for different rescue actions can be seamlessly corporate and allocate resources effectively.

The EO data should be integrated into the COP for prompt sharing. The current technology allows the file transfer of large formats of EO data via cloud, streaming directly over the network is another option. By breaking down the large pixel size image into smaller and tiled formats, web map technologies like WebGL, Cesium or OpenLayers allow real time streaming and visualization of the tiled imagery data. This approach reduces the initial download time and allows users to access and interact with the imagery data on-the-fly. Using the technologies of block-level storage and pyramid tiling methods for initial preview in lower resolution, the data format of Cloud-based Optimized GeoTIFF (COG) is available for faster data streaming (COGEO, 2024). Additionally, using open-source formats for sharing is recommended. This approach enables government departments to access the information more easily, enhances data exchange and collaboration between them, and reduces the risk of system failures during peak times. (DSIT, 2012).

In addition to the technology itself, an efficient data-sharing mechanism or a consent-based data exchange gateway among government departments and EO data providers is recommended. This would facilitate the exchange of EO data stored in various departments or image providers, ensuring that data is shared only after obtaining consent prior to a disaster. It can shorten the data acquisition time, facilitate efficient data access, and seamless integration with existing systems among government departments. Moreover, commercial satellite image providers commonly offer government licenses or even free usage of their imagery data in response to disasters (CASC, 2022; Planet Labs PBC, 2024; Maxar, 2024), leveraging the full potential of EO data governance in emergencies.

4.1.2 Provide Alternative Data Collection Option

The affected area cannot be accessed safely during and after the natural hazards because of falling trees, landslides, and road blockage. There may be safer solutions than deploying a ground inspection team to collect first-hand information on inaccessible areas or most damaged regions. The popularization of drones equipped with optical sensors provides an alternative option to understand the affected area by capturing the site photo and video. It has become popular for governments in both developed and developing countries such as the US, Japan, and Vietnam, to establish a drone team to undertake a rapid damage assessment after a disaster (Akhloufi et al., 2021; Mikio, 2024; Duong, 2023). Compared with ground inspection, the drone captures more spatial information in a shorter time, the ability to generate the orthophoto, maps, and other ARD products allows the subsequent review of complicated damage assessment.

Given the popularization of drone use, the Small Unmanned Aircraft (SUA) Order (Cap. 448G) with a restricted flying zone took full effect in Hong Kong on 1 December 2022 to seize the immense potential of SUA application while safeguarding aviation and public safety (HKSAR Government, 2022). Considering the principle of SUA Order and demand of using drones in response to disasters, there are also needs in preparing disaster-specific regulations or establishing protocols to enforce airspace rules, air traffic control, lifting restricted flying zones temporarily and controlling the sharing and use of drone data with coordination across government and non-government sectors. (Greenwood et al., 2020). It can allow prompt response and more efficient allocation of resources to areas most in need.

Additionally, one of the measures of drone management in response to the disaster is to set up an electric fence to control the air traffic in the affected area. Any authorized drones for rescue purposes are allowed to enter, while those without authorization will be prohibited from entering the fence-off area. Similar to the air traffic management system for aircraft, electric fences require a cloud-based system connecting all registered drones with geofencing technologies to monitor the flight data; the system can incorporate an alarm function when these drones fly into a restricted electric fence zone. A similar practice has been governed in the Interim Provisions on Light and Small Unmanned Aircraft Operations (UAS Operation Provisions) issued by the Civil Aviation Administration of China (CAAC) in December 2015.

4.1.3 Identify Affected Area with Analytic

Typhoons and heavy rainstorms often lead to flooding, especially when heavy rainfall occurs hourly, posing significant threats to low-lying areas. Synthetic Aperture Radar (SAR) data can be used to identify flooding areas during or after the heavy storms by comparing the SAR data before, during, and after the event. Water surfaces typically have lower backscatter signals than dry land, making them easily identifiable in SAR images. Integrating with the topographic map, the extent of flooding can be delineated. Compared with optical imagery, the SAR signals are able to penetrate the cloud, regardless of time, allowing for near real-time monitoring of flood events. CUHK demonstrated the use of three Gaofan-3 SAR images to identify the severe flooding area (CUHK, 2023). The identification of black spot areas (flooding areas) is important to government departments who need to evacuate residents, pile sandbags, and install water-stop boards. Besides, the airborne thermal infrared data can provide a broader, regional perspective on the local temperature and heat/cold stress patterns across an affected area (Janet et al., 2012). This information can help identify the communities and neighborhoods experiencing the most extreme temperatures, highlighting the areas with the greatest need for temporary heat or cold shelters. Thus, it can be used as an indicator to determine the demand and supply of Community Halls or Community Centers as temporary heat or cold shelters to provide temporary accommodation to people who need to take refuge from the heat and cold.

4.2 Precise and Persistent Monitoring

4.2.1 Support Coastal Management and Sponge City Initiatives

Numerous tide gauge stations monitor tidal levels in Hong Kong (HKSAR Government, 2024), and provide a continuous record of sea level changes over time. This data is essential for monitoring long-term trends and understanding the impacts of climate change on sea level rise. However, the tide gauge stations are limited to specific coastal locations, so the measured levels may not represent other regions without stations.

Satellite and aerial data such as LiDAR and imagery can complement the in-situ tide gauge measurements and extend the coverage to areas without direct observations. A clear workflow is demonstrated to integrate Landsat images with the tide gauge network, generate terrain models, and provide sea level data for regions where direct measurements are unavailable (Robbi et al., 2021). Use of Airborne LiDAR data is also common for shoreline mapping and coastal management (Wang et al., 2023). The Cartographic and Geologic Institute of Catalonia (ICGC) demonstrated the case of mapping an area from 50m inland to 10m water depth of the Catalan coastal zone using airborne LiDAR bathymetry (ALB) as a baseline for continuous coastal monitoring, proving its data collection ability in both land and low-depth sea area (Charles et al., 2023). Another example is that NOAA from the US has identified the flood risk and has monitored the coastal change using LiDAR since the mid-1990s to form part of the United States Interagency Elevation Inventory and created the Coastal LiDAR Data holdings as publicly available (NOAA Coastal Services Center, 2012; NOAA Office for Coastal Management, 2023).

The EO data provides the scientific foundation to strengthen the findings on urban coastal preventive measures. This precise data can support coastal risk assessments or shoreline management studies to identify low-lying or windy residential areas with higher risks (HKSAR Government, 2022). It can be used as a parameter to test, or model proposed mitigation measures, such as determining the optimal height and location of new coastal barriers or man-made seawalls, as well as the appropriate formation level of reclamation. Using LiDAR data as one of the topographic and bathymetric data, it provides an as-built survey for spectral wind-wave model to simulate the growth, decay, and transformation of wind-generated waves and swell, wave overtopping analysis and coastal flood inundation assessment to identify the area vulnerable to coastal risk (Dongmei et al., 2019; Nederhoff et al., 2024). This information can then inform the formulation of improvement works and management measures to prevent waves and floods from directly impacting the public, safeguarding public safety.

Furthermore, the development of sponge city is one of the resilience measures to alleviate the impact of coastal hazards (WSP, 2024). From the flood management perspective, this initiative is for the city to function like a sponge during rainy periods - absorbing, storing, filtering, cleaning, reusing, and controlling the discharge of rainwater, then using it as needed to improve ecological function and reduce flooding, thereby reducing the need for grey infrastructure, the large-scale artificial drainage infrastructure.

To put the sponge city concept into practice, some sponge city features will be incorporated into urban development projects. These features include rainwater gardens, urban lakes, and wetlands to retain flood water and revitalize water bodies. These sponge city features will be combined with sustainable drainage elements such as green roofs and porous pavement (Stephan, 2021). EO data can serve multiple functions to support the proactive placement and design of suitable sponge city features. EO data not only acts as a data source to improve simulation models, but also provides a way to evaluate the effectiveness of green infrastructure in enhancing the city's water infiltration and storage capabilities (FAO, 2023). The trend of EO sensors supporting hyperspectral image capturing provides a valuable tool for identifying unique spectral signatures from vegetation species. This data can be used to map the spatiotemporal distribution and characteristics of vegetation species over vast areas. Additionally, LiDAR with near-infrared wavelengths is able to collect multiple returns from ground surfaces. By monitoring changes in vegetation over time, EO data can measure the tree canopy, tree height and other tree inventory information. Furthermore, evapotranspiration, the combined process of soil evaporation and plant transpiration, is a crucial component of the water cycle and plays a significant role in the water-holding capacity of sponge cities. Multi-source EO data can be used to estimate the land evapotranspiration rate (Zheng, 2022). All these data facilitate the assessment of the green infrastructure's growth, survival, and overall performance.

Currently, the spatial resolution and temporal resolution of spaceborne hyperspectral sensor may be too low to support individual tree analysis. To address this issue, public sector, i.e. EO-1 hyperion (EROS, 2019), and commercial sector, i.e. Tanager-1 (Planet Labs PBC, 2024) and Pixxel (Pixxel, 2024) start to launch a sub-meter to meter grade resolution of hyperspectral sensor. In contrast, recent studies have demonstrated the use of airborne or in-situ hyperspectral data to determine the species information. Hou et al. combined spatial and spectral information collected by hyperspectral sensors mounted on drones of the Chinese Academy of Surveying and Mapping in the Tiegang Reservoir Dataset, resulting in a spatial and spectral resolution in 0.1m and 5nm in 112 bands respectively. Abbas et al. collected tree spectral information from the handheld hyperspectral camera to evaluate the tree information with several indexes. Laurin et al. demonstrated the use of in-situ spectra measured by a spectrometer to compare with spectra of tree tops measured from Sentinel-2 satellite images for a forest phenology study.

4.2.2 Strengthen the Slope

Slopes in Hong Kong can be differentiated into natural terrain and man-made slopes. Natural terrain defines the hillsides that human activities have not substantially modified, while man-made slopes are formed by cutting into hillsides and/or earthfilling. Over 60% of the area in Hong Kong is defined as natural terrain (CEDD, 2016). CEDD is responsible for regular inspection and preventive maintenance of government slopes, requiring private owners to fulfill their duties in maintaining their slopes and exercising geotechnical control on public works and private development projects to ensure slope safety (CEDD, 2019). Natural terrain landslides, such as open hillslope landslides, channelized debris flow, and debris floods, are common in Hong Kong (NG et al., 2018), especially after extreme storm and typhoon. As the consequences of landslides pose a great threat to human life and property, preventive measures and identification of potential landslide areas become essential. EO data has become an indispensable data source for early identification and monitoring of landslide-prone areas. Detailed interpretation of aerial photos, while often hindered by dense vegetation cover, can still provide valuable insights into the terrain's condition, such as the presence of cracks and other subtle signs that precede larger-scale slope failures (Guzzetti et al., 2012). The advent of airborne LiDAR technology has significantly enhanced this capability, enabling the creation of high-resolution digital terrain models that can penetrate the vegetation canopy and reveal the underlying landform features (Razak, 2011).

The Enhanced Natural Terrain Landslide Inventory (ENTLI) compiled by the GEO demonstrates the power of aerial photos with aerial photo interpretation and advanced GeoAI techniques for systematic identification (GEO, 2020). By training the annotated landslide on aerial photos, quantitative risk assessments can be conducted to diagnose the risk characteristics of natural terrain landslides and devise a risk-based prioritization system to identify the area with higher landslide risk to follow up under Landslip Prevention and Mitigation Programme (LPMitP) (GEO, 2021). LPMitP allows the authorities to implement appropriate landscape treatments and soil bioengineering measures to minimize the impact of potential slope failures (Choi et al., 2018). While these measures may not be sufficient to cover all large-scale and rare landslide events, they can significantly reduce the overall risk and provide additional time for evacuation and emergency response.

Very high-resolution of satellite images and aerial photos allow for non-invasive inspection of man-made slopes, identifying subtle changes, cracks, and other signs of distress that may precede a catastrophic failure (Jaboyedoff et al., 2012). However, high-rise buildings blocked line of sight, generating significant geometric distortion and shadow, thus increase the difficulties in forming the terrain model, airborne LiDAR data with higher density is the way to overcome it, it can generate highly accurate, 3-D models of man-made slopes, revealing the precise geometry, structural integrity, and any deformations that may be occurring (Lato et al., 2015). By establishing comprehensive baseline data and monitoring these slopes over time, maintenance responsible parties can use it to assess the stability of retaining walls and cut slopes and design appropriate retrofitting or reinforcement measures. Together with other spatial data, i.e., topographic map and SIMAR slope polygon (SMO, 2024), the government departments can detect emerging issues and take statutory actions through an ordinance to ensure its rectification under the LPMitP.

Apart from airborne LiDAR, more LiDAR sensors have been launched into space, providing wider coverage, and better temporal resolution when the sensor accuracy has been improved. This satellite LiDAR data is combined with other ground-based monitoring techniques, such as GPS sensors and ground-based LiDAR scans, to provide a comprehensive view of slope stability in areas prone to landslides. Specifically, the Canadian Forest Service and Natural Resources Canada from the Canadian Government have been using altimeter data from ICESat-2 together with Airborne LiDAR to generate territory-wide high-resolution digital elevation models and slope maps (Natural Resources Canada, 2023). It can be used to monitor landslide and slope stability on a regional basis persistently.

SAR has the advantage of detecting small ground movements. By analyzing a series of SAR images and employing data processing techniques—such as interferogram generation and phase unwrapping—Persistent Interferometric SAR (PInSAR) enables the quantification of displacement and the early identification of potential instability in the ground. However, high-rise buildings in urban environments like Hong Kong can cause significant radar signal scattering multipath and shadowing effects, which reduce the effectiveness of SAR data collection on the ground (Zhao et al., 2016; Yang et al., 2016). Given these factors, applying SAR technology in larger flat areas and regions with lower building density is more effective. Such environments reduce the impact of signal interference, allowing for more precise and reliable data interpretation, ultimately enhancing the effectiveness of monitoring geological stability and urban infrastructure.

4.2.3 Monitor the Land Cover Change for Regional Land Management

Land cover map (LCM) describe the physical material and man-made features on the surface of the Earth. This information goes beyond just identifying land use – it also captures the physical characteristics of the landscape, including vegetation type, density, and health according to a well-defined nomenclature and classification scheme (FAO, 2024). By mapping these attributes across large geographic areas, land cover data creates a detailed spatial inventory of the natural and built environments.

LCM can be used to identify vulnerable hotspots and precisely target adaptation interventions, it provides a detailed, spatially explicit understanding of the region’s current environmental conditions and landscape characteristics across a region. This information can be used to pinpoint areas that are particularly vulnerable to the impacts of climate change such as the low-lying coastal areas, impervious surfaces and green infrastructures, marginal agricultural lands, and high wildfire risk areas. With a clear understanding of vulnerable hotspots, LCM can guide the targeted deployment of adaptation interventions. This can analyze the optimal locations of various measures like flood barriers, wildfire breaks, or green infrastructure to protect high-risk areas. Land cover information can also inform the design and placement of these interventions to ensure they are well-suited to the local environmental conditions. Spatial-temporal land cover mapping enables the persistent monitoring of landscape changes, such as urbanization patterns in suburban areas and deforestation rate in protection zones or shifts in vegetation – crucial for evaluating the efficacy of adaptation efforts.

Development of robust, up-to-date LCM relies on integrating various EO data sources and cutting-edge analytical methods, including GeoAI. A common approach is to leverage satellite imagery, to conduct land cover classification across rural and natural areas, as demonstrated by programs like the European Union's CORINE Land Cover, supported by the European Space Agency (ESA). Meanwhile, the US Geological Survey (USGS) cyclically updates its 30-meter National Land Cover Database (NLCD) using Landsat satellite data in US. Moving to higher resolutions, the Chesapeake Bay Program in the US has created detailed 1-meter land use and land cover maps by combining National Agriculture Imagery Program (NAIP) aerial imagery with LiDAR-derived height data. Similarly, the UK Centre for Ecology & Hydrology (UKCEH) publishes a national-scale 10-meter land cover map of the UK using Sentinel satellite imagery. Beyond national-level efforts, local initiatives have also leveraged advanced EO technologies - for example, government-funded studies in Japan (Naoto et al., 2024) and Singapore (Gaw et al., 2019) have showcased the use of deep learning algorithms like U-Net to generate sub-meter LCM from very high-resolution aerial and satellite imagery. In Hong Kong, the Agricultural and Fisheries and Cultivation Department (AFCD) and the Chinese University of Hong Kong (CUHK) explore the potential of using Worldview satellite images to identify and map major terrestrial habitats in Hong Kong (Kwong et al., 2022). The Planning Department (PlanD) of the HKSAR Government funded a project to develop a workflow to combine land use and land cover from mid-resolution satellite images to form a Utilization Map (Remote Sensing Laboratory, 2024). Thus, integrating diverse EO data sources, from medium-resolution satellites to high-resolution aerial and satellite imagery, combined with cutting-edge analytical methods, enables land management authorities to develop comprehensive, multilayered LCMs that support precise, data-driven climate resilience strategies.

The development of effective LCM faces several critical challenges that must be addressed to ensure their persistent use and impact. Firstly, it is essential to clearly define the objectives and desired outcomes of the LCM, aligning it with the specific needs of land management authorities and urban planners such as land utilization use, habitat map and vegetation map, and requiring a deep understanding of the decision-making contexts in which these maps will be applied. Secondly, establishing well-defined, hierarchical nomenclature and classification schemes is crucial to combat the inherent complexity of real-world land cover conditions. Dynamic and adaptable classification systems are needed to accurately capture the nuances and changes in land cover, especially in rapidly evolving urban and peri-urban environments. Ensuring persistent monitoring and accounting for the relatively short lifespans of many satellite platforms further complicates maintaining up-to-date, time-series LCMs. Selecting suitable EO data sources is another critical challenge, as different sensor types, spectral resolutions, and spatial scales can significantly impact the accuracy and granularity of LCMs. Integrating multi-source EO data, such as satellite imagery, SAR data, and aerial orthophotos, hyperspectral data, requires understanding the strengths and limitations of this diverse dataset, i.e., availability of data, the capability of workflow, artifacts of data etc. Design of a harmonized workflow is required to address the limitations and maximize the strength of each of this dataset. Finally, the prediction performance of advanced analytical techniques, such as deep learning models, heavily depends on the quality of the training data, and accuracy assessment. Establishing comprehensive, high-quality land cover labeling and validation datasets, potentially with the support of field-based spectroscopic measurements, i.e., spectrometers, along with rigorous accuracy assessments for fine-tuning hyperparameters and evaluating sufficient sampling results, are essential to unleashing the full potential of these cutting-edge GeoAI methods.

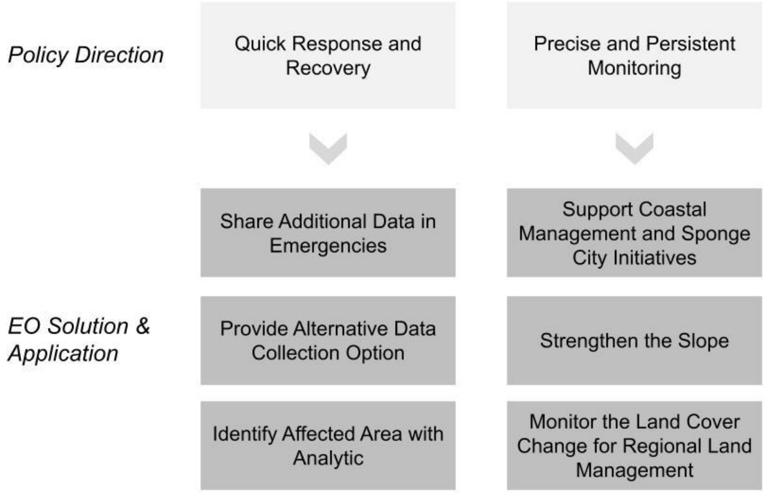

Figure 3 - The Summary of Recommended Policy Direction and Respective EO Solutions and Applications

5. CONCLUSION

In addressing climate change issues, remote sensing technology makes EO data available to support quick responses before climate events arrive and quick recovery after hazards like superstorms and typhoons in Hong Kong. Additionally, EO data enables precise and persistent monitoring of rising sea levels, identifying low-lying areas and potential landslides, mapping of habitat and vegetation coverage, and rising urban temperature. To effectively use the EO data in implementing climate resilience and adaptation policies in Hong Kong, best-practice surveys are crucial to ensure accurate data collection, completeness of processing workflow, consistent results and quality deliverables, creating a reliable foundation for injecting EO data and other geospatial data from insight to implementation that generate significant long-term benefits to our living environment.

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