Leveraging Space Science and Technology for Climate-Induced Disaster Management in Pakistan

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Abstract

The frequency and severity of climate-related disasters, such as floods, droughts, heatwaves, and glacier melt, are on the rise and pose serious threats to vulnerable countries. Due to warming temperatures, changing rainfall patterns, and glacier melting, Pakistan is facing increased risks to its agriculture, water resources, infrastructure, and human security. This paper discusses how space science and technology can play a pivotal role in improving Pakistan's ability to deal with climate-led disasters. It also examines the institutional arrangements, technological tools, and national politics that facilitate the integration of Earth Observation (EO), satellite remote sensing, Geographic Information Systems (GIS), and Artificial Intelligence (AI) in Disaster Risk Reduction (DRR) and Early Warning Systems (EWS). Efforts of Space and Upper Atmosphere Research Commission (SUPARCO), its collaborations with national and international agencies, satellite programs like Remote Sensing Satellite System (PRSS) and Pakistan Remote Sensing Satellite - Earth Observation 1 (PRSC-EO), as well as its contribution to research initiatives like the Space Application Center for Response in Emergency and Disaster (SACRED) and the Natural Catastrophe Modelling (NatCat) initiative are discussed in detail in this study. Drawing on international best practices from countries such as China, Japan, and the United States, this paper examines how emerging technologies like big data analytics, Machine

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Learning (ML), and high-performance computing are transforming disaster management. While Pakistan has made significant progress in this area, it still faces major challenges, including a lack of satellite infrastructure, inadequate funding, poor inter-agency coordination, and difficulties with last-mile data application. The paper concludes that with continued investment, improved institutional cooperation, and capacity-building efforts, Pakistan can effectively leverage space-based solutions to enhance climate resilience and reduce disaster risks.

Keywords: Space Science, Earth Observation, Climate Change, Natural Disasters, Pakistan

Introduction

Climate change has become one of the major issues of the twenty-first century, and its effects are becoming more noticeable due to the increasing rate and intensity of natural disasters like floods, droughts, heat waves, and wildfires. In addition to causing massive human loss, these climate-related disasters also cause massive socio-economic losses, especially in developing countries where infrastructure and adaptive capacities are usually insufficient. Pakistan, located at the crossroads of various climate zones and unstable ecosystems, is especially susceptible. Whether it is the long-term drought in Balochistan, the devastating floods in Sindh, or the melting of glaciers in the highlands, the country is exposed to complex climate risks that endanger food security, water supply, human health, and national growth.

To counter these mounting threats, advanced technologies, particularly space-based technologies, like EO, GIS, and Satellite Remote Sensing (SRS), are becoming central. These technologies provide immeasurable assistance at every stage of disaster management. For example, they can support EWS, help conduct a quick damage assessment and guide the development of long-term resilience strategies. At the international level, other countries such as China, Japan, and the US have shown how the incorporation of space science in DRR systems can revolutionize response systems and reduce the effects of climate change.

In Pakistan, SUPARCO has been at the forefront in incorporating satellite-based technologies in the disaster management systems, such as the SACRED and NatCat Risk Modelling for major disasters of flood, drought, landslides, cyclones, and heatwaves. Nonetheless, these efforts are still faced with challenges such as insufficient satellite resources, reliance on foreign launch services, and data integration and policy implementation gaps. This study aims to assess the role of space science and technology in climate-related disaster management in Pakistan, outline the current institutional frameworks, technology, global good practices and policies, as well as define the key challenges and future development opportunities.

Climate Change and Disaster Risks

Climate Change is a long-term change in weather patterns across land, ocean, and atmosphere, and is considered one of the most significant global challenges in today's world. It affects various sectors, including agriculture, biodiversity, human health, and the economy. It results from both natural aspects, like volcanic eruptions, and anthropogenic activities such as deforestation and burning fossil fuels. This has led to extreme weather events, sea-level rises, and shifts in ecosystems, which threaten species' survival and biodiversity. Its impacts are felt globally, but the degree of impact varies, based on regional factors and the level of disaster preparedness.[1] Hence, there is a need to adopt interdisciplinary approaches combining AI, data science, environmental science, and policymaking to address climate change.[2]

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[1] Abbass, Kashif, Muhammad Zeeshan Qasim, Huaming Song, Muntasir Murshed, Haider Mahmood, and Ijaz Younis, "A review of the global climate change impacts, adaptation, and sustainable mitigation measures" *Environmental science and pollution research* 29, no. 28 (2022), pp. 42539-42559. https://link.springer.com/article/10.1007/s11356-022-19718-6

[2] Ahmed Hussein Ali and Rahul Thakkar, "Climate Change Through Data Science: Understanding And Mitigating Environmental Crisis," *Mesopotamian Journal of Big Data* Dec 2 (2023), pp. 125-137, https://mesopotamian.press/journals/index.php/bigdata/article/view/177

The increasing severity and frequency of natural disasters, exacerbated by climate change, have highlighted gaps in current disaster management systems. Traditional disaster response approaches are often inadequate for managing the complexity and unpredictability of modern disasters.[3] Climate-related disasters affect developing countries the most, where vulnerable populations are increasingly threatened by rising temperatures and unpredictable weather patterns. Vulnerability to climate change is driven by poor socioeconomic conditions, exposure to risks, and the lack of disaster management systems.[4] The Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Report (AR6) synthesizes the current state of knowledge regarding climate change, its impacts, risks, and potential mitigation and adaptation responses.[5] The document highlights that despite the advancements made in adaptation activities, there are still major gaps. Although there are some policy improvements, the existing national commitments are not sufficient to keep global warming to 1.5°C or even 2°C. It stresses that mitigation and adaptation solutions exist, but the time to act effectively is running out, and the world needs to act now.

Regional Vulnerabilities and Disaster Trends

Arid and Semi-Arid (ASA) regions cover 41% of the Earth's land surface and are home to approximately 2.5 billion people. These regions often face challenges like irregular climatic conditions, droughts, and political instability.[6] South Asia is highly vulnerable to natural hazards, with over

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[3] Justin Diehr, Ayorinde Ogunyiola, and Oluwabunmi Dada, "Artificial Intelligence and Machine Learning-Powered GIS for Proactive Disaster Resilience in a Changing Climate," *Annals of GIS* (2025), pp. 1–14; Ibrar ul Hassan Akhtar, "Managing Urban Flooding," (2017), https://tribune.com.pk/story/1502156/managing-urban-flooding/; Ibrar ul Hassan Akhtar, "Pakistan Needs a Fresh Disaster Mitigation Strategy," (2015), http://www.scidev.net/global/disasters/opinion/pakistan-disaster-mitigation-strategy.html

[4] Linpei Zhai and Jae-Eun Lee, "Investigating Vulnerability, Adaptation, And Resilience: A Comprehensive Review Within the Context of Climate Change," *Atmosphere* 15, no. 4 (2024), p. 474 (April 11, 2024). https://www.mdpi.com/2073-4433/15/4/474.

[5] Intergovernmental Panel on Climate Change (IPCC), *Climate Change 2023: Synthesis Report, Summary for Policymakers. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. Core Writing Team, H. Lee, and J. Romero (Geneva: IPCC, 2023), https://mural.maynoothuniversity.ie/id/eprint/17886/1/IPCC_AR6_SYR_SPM.pdf

[6] Sarchil Hama Qader, Jadu Dash, Victor A. Alegana, Nabaz R. Khwarahm, Andrew J. Tatem, and Peter M. Atkinson. "The Role of Earth Observation in Achieving Sustainable Agricultural

70% of its population living in poverty, and faces increasing vulnerability due to urbanization, environmental degradation, and political instability.[7] The region has high economic losses from disasters, with Average Annual Losses (AAL) reaching over USD 153 billion. Countries like Bangladesh, India, and Nepal experience the highest losses relative to their GDP.[8] Natural disaster management challenges in South Asia include a lack of preparedness, inefficient EWS, poor infrastructure, limited resources, and coordination challenges. This emphasizes the need for targeted interventions like the integration of DRR and Climate Change adaptation (CCA) into national policies to improve the resilience of South Asian countries.[9]

The region has flood-prone countries that have distinct geographic and climatic features, which lead to a variety of floods, including riverine and flash floods. Such floods tend to cause extensive loss of lives and destruction of crops, infrastructure, and local economies, which are particularly devastating in low-income and highly populated regions. Conversely, droughts are among the most complicated and least studied natural hazards, which impact more individuals in the world than any other category of disaster. Droughts are influenced not only by meteorological abnormalities like a deficit of precipitation but also by anthropogenic activities like unsustainable land use, water management, and bad governance. Droughts are especially hard to track and react to, due to their slow-onset nature, which can result in a delayed response and a long-term

Production in Arid and Semi-Arid Regions of the World," *Remote Sensing* 13, no. 17 (2021), pp. 3382. https://www.mdpi.com/2072-4292/13/17/3382

[7]Shesh Kanta Kafle, "Disaster risk management systems in South Asia: Natural hazards, Vulnerability, Disaster Risk and Legislative and Institutional Frameworks," *Journal of Geography & Naural Disasters* 7, no. 207 (2017), pp. 2167-0587. https://www.researchgate.net/publication/321228880_Disaster_Risk_Management_Systems_in_South_Asia_Natural_Hazards_Vulnerability_Disaster_Risk_and_Legislative_and_Institutional_Frameworks

[8]ESCAP, UN, "The Disaster Riskscape Across South Asia: Key Takeaways for Stakeholders," (2020). https://www.unescap.org/sites/default/d8files/knowledge-products/IDD-APDR-Subreport-SSWA-v1-8-P.pdf

[9]Muhammad Ahsan Samad, Kadir Arifin, and Azlan Abas. "A systematic literature review on the challenges of Southeast Asian countries in natural disaster management," *Cogent Social Sciences* 11, no. 1 (2025) https://www.tandfonline.com/doi/epdf/10.1080/23311886.2024.2435590

socio-economic effect especially in agrarian societies. Such accumulating weaknesses require the application of superior technologies like space-based Earth Observation Systems (EOS), which may assist in tracking climatic trends, early warning indicators, and evidence-based policy responses in the South Asian region.

Pakistan's Climate Vulnerabilities

Pakistan faces increased climate risks, including temperature rise, glacier retreat, altered rainfall patterns, and more frequent extreme weather events such as floods and droughts. The Indus Delta is vulnerable to rising sea levels, coastal erosion, saline intrusion, and increased flooding, threatening agriculture (food security) and biodiversity.[10] Pakistan's vulnerability to climate change has increased since 1999, with many extreme climate events affecting water resources and agriculture. The recent extreme events in Pakistan are floods (2010, 2013, 2014, 2015, and 2022) and a long-term drought in 1998-2002, which have severely affected the agriculture, water resources, infrastructure, and livelihoods in Pakistan, indicating the increasing vulnerability of the country to climate change.[11]

Pakistan experienced record-breaking monsoon rainfall in 2022, leading to severe flooding, particularly in the provinces of Sindh and Balochistan. Climate change has likely increased rainfall intensity by up to 50%.[12] Communities living near glaciers face the brunt of these natural hazards. Despite low carbon footprints, these communities are highly vulnerable to

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[10]Rasul, Ghulam. "Climate data and modelling analysis of the Indus region," *Pakistan Meteorological Department* (2012).https://wwfasia.awsassets.panda.org/downloads/climate_data_modelling_analysis_of_the_indus_ecoregion.pdf

[11] Sohail Abbas et al., "Spatial-Temporal Seasonal Variability of Extreme Precipitation under Warming Climate in Pakistan," *Atmosphere* 14, no. 2 (2023): 210, https://www.mdpi.com/2073-4433/14/2/210

[12] Friederike E. L. Otto et al., "Climate Change Increased Extreme Monsoon Rainfall, Flooding Highly Vulnerable Communities in Pakistan," *Environmental Research: Climate* 2, no. 2 (2023): 025001, https://iopscience.iop.org/article/10.1088/2752-5295/acbfd5.

the consequences of climate change.[13] The 2022 mega-flood in Pakistan was one of the most severe, affecting two-thirds of the country and causing considerable damage to agriculture, infrastructure, and livelihoods. Climate Change is also impacting mountainous areas, which are extremely sensitive to climate change, with visible indicators like glacier retreat and temperature shifts. These changes have significant implications for water supply, biodiversity, and infrastructure.[14]

Besides environmental impacts, climate-related catastrophes in Pakistan have led to serious socio-economic impacts such as mass displacement, poverty, destruction of essential infrastructure, and agricultural losses. The agriculture sector, which supports a significant number of people in the rural areas of Pakistan, is especially vulnerable to altered precipitation patterns and rising temperatures. In the same way, glacier melting and erratic hydrological cycles pose a threat to the energy and water security of the country. These interrelated weaknesses require a multi-sectoral and science-based response. Although Pakistan has advanced in climate adaptation planning with policy tools such as the National Climate Change Policy and the National Adaptation Plan, implementation is disjointed and under-funded. The combination of space-based technologies, including EO and remote sensing, offers a pivotal possibility to strengthen the disaster risk reduction and EWS in the country.

Space-Based Technologies for Disaster Management

Satellite remote sensing is important in delivering timely and precise data in disaster preparedness, response, and recovery. The rising rate and intensity of climate-related disasters require new and prompt solutions to disaster management. Technologies like Synthetic Aperture Radar (SAR)

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[13] Misha Shahid, "Confronting Glacial Hazards: A Study of Disaster Impact and Community Adaptation to Glacial Lake Outburst Floods in Hunza, Pakistan," PhD diss., *Massachusetts Institute of Technology*, 2024. https://dspace.mit.edu/handle/1721.1/156156

[14] Thomas Kohler and Daniel Maselli, "*Mountains and climate change. From Action Understanding"*, Geographica *Bernensia*, 2009. https://www.activeremedy.org/wpcontent/uploads/2014/10/kohler_t._et_al_2009_%E2%80%98mountains_and_climate_change.pdf

are especially useful, since they can be used to acquire high-resolution imagery independent of cloud cover or lighting, and are therefore invaluable during flood events, cyclones, and other rapidly changing hazards. Such systems enable authorities to evaluate the effects of disasters in near real-time, distribute resources more efficiently, and introduce informed relief measures.[15]

In addition to the observation satellites, the use of Information and Communication Technologies (ICTs) like the Flood Early Warning Systems (FEWS) has enhanced the ability to predict, track, and act on the hydrometeorological threats.[16] When coupled with Geo-Information Technologies (GIT) such as Remote Sensing (RS), GIS, and Global Positioning System (GPS), disaster managers have an effective set of tools to detect hazards, map risks, and assess damage after the event. The technologies facilitate multi-hazard monitoring and allow decision-makers to visualize risk in both spatial and temporal dimensions, which helps in rapid response and long-term planning.[17]

Nevertheless, disaster management is not only a matter of technological capacity. The perception of disaster risks, i.e., how people and communities learn to interpret and react to risks, is the central factor that determines preparedness and behavioral response. Research has shown that the more a population is aware of the dangers of floods, the more likely they are to take precautionary measures, evacuate early, and recover quicker. Unfortunately, there is still a disconnect between the real risk and perceived risk in most

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[15] Julie Rolla et al., "Satellite-Aided Disaster Response," *AGU Advances* 6, no. 1 (2025), https://doi.org/10.1029/2024AV000109; Ibrar ul Hassan Akhtar and H. Athar, "Contribution of Changing Precipitation and Climatic Oscillations in Explaining Variability of Water Extents of Large Reservoirs in Pakistan," *Scientific Reports* 9, no. 1 (2019), https://doi.org/10.1038/s41598-019-50020-1 ; Ibrar ul Hassan Akhtar and H. Athar

[16] Farhan Shafiq and Kamran Ahsan, "An ICT-Based Early Warning System for Flood Disasters in Pakistan," *Research Journal of Recent Sciences* 3, no. 9 (September 2014): 108–118, http://www.isca.in

[17] M. Hussain, Mudassar Hassan Arsalan, Kashif Siddiqi, and Bushra Naseem, "Emerging Geo-Information Technologies (GIT) for Natural Disaster Management in Pakistan: An Overview," in *Proceedings of the 2nd International Conference on Recent Advances in Space Technologies (RAST 2005)*, 2005, 204–209, https://doi.org/10.1109/RAST.2005.1512618

vulnerable areas. The result of this disconnect is frequently poor individual preparedness, opposition to early warning, and poor community-based response plans. To fill this gap, it has increasingly been acknowledged that technological solutions should be supported by community involvement, education programs, and risk communication at the local levels. Space-based tools can be critical in the process, as they can visualize the hazards in an accessible way and alter risk information to specific geographic and social situations. Finally, the combination of space-based advanced technologies and inclusive disaster risk governance can become a powerful tool to enhance national and local capacities to manage climate-induced disasters.

Emerging Technologies and Global Best Practices

The rising complexity and severity of climate-related disasters have triggered the adoption of emerging technologies in disaster risk management systems across the globe. One of the most revolutionary advancements is the application of high-performance computing (HPC) to process and analyze the large amounts of satellite data collected by polar-orbiting and geostationary EO satellites. HPC greatly improves the rate and accuracy of disaster detection and allows real-time creation of geospatial products needed to provide early warnings, situational awareness, and coordinated response.

Additionally, these developments have been revolutionized with the emergence of Big Data analytics, which have transformed disaster monitoring and forecasting. Big Data technologies can keep track of the disaster evolution and the community-level vulnerabilities by combining observations of satellite images, sensor networks, crowdsourcing, and even social media. AI, along with machine learning (ML) and deep learning (DL) algorithms, are gaining more prominence in such platforms, and they can enhance pattern identification, risk evaluations, and optimize the decision-making process in case of an emergency.[18]

[18]Manzhu Yu, Chaowei Yang, and Yun Li, “Big Data in Natural Disaster Management: A Review,” *Geosciences* 8, no. 5 (2018): 165, https://www.mdpi.com/2076-3263/8/5/165

The examples of global best practices of countries like China, Japan, and the US demonstrate how the integration of satellite systems, AI, and geospatial intelligence can be used to create robust integrated disaster management ecosystems. For example, the small satellite constellations of China and the EO satellites of Japan, used to conduct post-disaster surveys, demonstrate the potential of highly developed technology to offer real-time surveillance and high-resolution damage evaluation. The models provide important lessons to countries like Pakistan, where space-based systems are still developing. The NatCat Risk Modeling project of SUPARCO is a step in the right direction, and the project is expected to replicate such international standards by using localized satellite data to map hazards and assess vulnerability.[19]

Moreover, there has been significant advancement in post-disaster damage assessment using satellite imagery, unmanned aerial vehicles (UAVs), and LiDAR technologies. Convolutional Neural Networks (CNNs) and deep learning architectures have become the most common ML models to identify and categorize structural damage more quickly and accurately. Nevertheless, the fusion of multi-source data is still a significant challenge due to differences in spatial resolution, data formats, and imaging conditions, which makes the seamless fusion of data difficult and slows down its operational implementation.[20]

Technologies Used	Purpose	Key Benefits
Satellite Imagery (SAR, Optical)	Building damage assessment, disaster monitoring	Large-scale damage detection, continuous monitoring
UAV-based Imagery	High-resolution damage analysis, building inspection	Detailed surface damage, portability, and flexible deployment

[19] Amna Rauf and Usman W. Chohan, *Role of Space Technologies in Disaster Risk Management: Lessons for Pakistan*, January 25, 2020, SSRN, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3530032

[20] Sultan Al Shafian and Da Hu, "Integrating Machine Learning and Remote Sensing in Disaster Management: A Decadal Review of Post-Disaster Building Damage Assessment," *Buildings* 14, no. 8 (2024): 2344, https://www.mdpi.com/2075-5309/14/8/2344

LiDAR (Light Detection and Ranging)	Structural integrity analysis, terrain mapping	High precision, weather-independent data collection
Machine Learning (ML)	Damage classification, model enhancement	Increased accuracy, automated damage detection
Deep Learning (DL)	Post-disaster building damage prediction	Improved detection in complex environments

Table 1: Different Technologies Integration for Disaster Management[21]

Following these trends, the use of AI in disaster prediction, monitoring, and response, especially in the case of floods, earthquakes, droughts, and wildfires, is gaining popularity worldwide. To increase the accuracy and timeliness of EWS, ML models and AI are being increasingly used to automate damage assessments based on satellite imagery and to provide support with scenario-based risk forecasting. States such as China, the US, India, and the United Kingdom (UK) are on the front line of disaster research using AI, with China being the leader in flood forecasting models and the US playing a major role in earthquake EWS. Although several AI models have demonstrated positive outcomes, there are still issues to be addressed, particularly regarding data quality, the accuracy of models, and the absence of real-time operational integration in disaster-prone areas.[22]

One of the most important developments in the area is the application of data fusion techniques, in which AI algorithms receive and merge information streams of multisource datasets (satellite imagery, ground sensors, and social media streams) to enhance disaster prediction and situational awareness. Besides improving decision-making, these tools can also produce fast visual results, which are essential to emergency managers and responders. However, the question of explainability of models, data privacy, and bias of algorithms is a major barrier to the large-scale adoption,

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[21] Al Shafian and Hu, "Integrating Machine Learning," 2344.
[22] Arief Wibowo, Ikhwan Amri, Asep Surahmat, and Rusdah Rusdah, "Leveraging Artificial Intelligence in Disaster Management: A Comprehensive Bibliometric Review," *Jàmbá: Journal of Disaster Risk Studies* 17, no. 1 (2025): 1–9, https://doi.org/10.4102/jamba.v17i1.1776.

especially in low-resource settings. To maximize the potential of AI in disaster management, they should be integrated into well-coordinated institutional frameworks, which are facilitated by high-performance computing infrastructure, transparent data-sharing practices, and capacity building.

Comparative Assessment of Pakistan's Space Development within Asia-Pacific Space Cooperation Organization (APSCO) Member States

The following table is drawn to compare the space capabilities and legal frameworks of the APSCO member states to evaluate the relative position of Pakistan in the regional space development.

APSCO Member State	National Space Agency	LEO Satellite Capability	GEO Satellite Capability	Satellite Launch Capability	Space Law	National Space Policy
China	China National Space Administration (CNSA)	Yes (1970)	Yes (1984)	Yes (1970)	Yes (2000)	Yes (2000)
Iran	Iranian Space Agency (ISA)	Yes (2005)	Yes (2011)	Yes (2009)	Yes (2012)	Yes (2005)
Pakistan	SUPARCO	Yes (1990)	Yes (2011)	No	Yes (2011)	Yes (2024)
Turkey	Turkish Space Agency (TSA)	Yes (1990)	Yes (1994)	No	Yes (2016)	Yes (2016)
Bangladesh	Space Research & Remote Sensing Organization (1980)	No	Yes (2018)	No	No	Yes (2009)
Mongolia	Communication and Information Technology	Yes (2017)	No	No	No	No

	Authority (CITA)					
Peru	National Commission for Aerospace Research and Development	Yes (2013)	No	No	No	Yes (2009)
Thailand	Geo-Informatics & Space Technology Development Agency	Yes (1998)	Yes (1993)	No	No	Yes (2016)

Table 2: National Space Agencies of APSCO Member States and Space Capacities

The above table provides a comparative analysis of space capabilities and governance systems of the APSCO member states. It points out the position of each national space agency, the ability to operate Low Earth Orbit (LEO) and Geostationary Equatorial Orbit (GEO) satellites, the national capability to launch its satellites, and the presence of national space laws and policies. China and Iran are among the members with full-spectrum space capabilities, including satellite launch. Although Pakistan and Turkey have operational LEO and GEO satellites and a space policy, they do not have launch capabilities. Whereas Thailand has a well-developed satellite operation but remains undeveloped in legal and launch aspects.

Space Science and Technology in Pakistan

Space science and technology, especially EO, are the outcome of nineteenth-century research. EO is the science of collecting data information about the Earth's surface through satellite and aerial platforms. Satellite data are essential for understanding the Earth's physical, chemical, and biological systems. Satellite EO evolution history began with topographic mapping in the 1840s, the emergence of satellite platforms, and gained prominence with National Aeronautics and Space Administration's (NASA) Landsat program, which began in 1972. The availability of open-access satellite data has democratized the use of EO data, especially in developing countries that lack the infrastructure for independent satellite launches.[23] In Asia, APSCO member states, along with Peru, have a long history in the domain of space science and technology for national development through space as a strategic sector.

Space science and technology, particularly EO tools, play a crucial role in implementing these development agendas by providing reliable data for monitoring and assessing progress toward Sustainable Development Goals (SDGs).[24] Pakistan's National Space Agency, SUPARCO, was established in 1961 to promote the applications of space science and technology in Pakistan through various sectors including environmental monitoring, agriculture and natural resource management, satellite communication, urban planning and infrastructure development, education, disaster management, remote sensing, and earth observation, etc. SUPARCO has been operating LEO and GEO since 2011, along with a National Space Policy; however, it lacks an indigenous satellite launch capability (see Table 1).[25]

SUPARCO utilizes satellite data for disaster management in Pakistan, enhancing mitigation, response, and relief operations.[26] The GIS has been used for disaster management; however, integrating AI and ML enhances its ability to analyze large datasets, predict disaster events, and support decision-making in real time. The study aims to explore how the integration

[23] Pratistha Kansakar and Faisal Hossain, "A Review of Applications of Satellite Earth Observation Data for Global Societal Benefit and Stewardship of Planet Earth," *Space Policy* 37 (2016): 46–54, https://www.sciencedirect.com/science/article/abs/pii/S0265964616300133

[24] A. Senthil Kumar, Sergio Camacho, Nancy D. Searby, Joost Teuben, and Werner Balogh, "Coordinated Capacity Development to Maximize the Contributions of Space Science, Technology, and Its Applications in Support of Implementing Global Sustainable Development Agendas—A Conceptual Framework," *Space Policy* 51 (2020): 101346, https://www.sciencedirect.com/science/article/abs/pii/S0265964619300761

[25] Yongliang Yan, "Capacity Building in Regional Space Cooperation: Asia-Pacific Space Cooperation Organization," *Advances in Space Research* 67, no. 1 (2021): 401–410, https://doi.org/10.1016/j.asr.2020.10.022

[26] Rahmatullah Jilani, Subhan Khan, Mateeul Haq, et al., "Pakistan 2010 Floods Monitoring Using MODIS Data," *Proceedings of the International Workshop on Recent Advances in Space Technologies (RAST)*, November 17–20, 2010. https://www.researchgate.net/publication/241277267_Pakistan_2010_Floods_Monitoring_Using_MODIS_Data_proceedings_17-20_November_2010

of GIS with AI and ML can improve disaster preparedness, response, and resilience, particularly in the face of a changing climate.[27]

Institutional Framework and SUPARCO's Role in Disasters

In its space applications program, SUPARCO has specifically focused on disaster risk management. In 2013, it created the SACRED to support disaster management authorities with satellite remote sensing and GIS technical assistance.[28] The mandate of SACRED is to monitor different natural hazards, produce early warnings, map the extent of disasters, and evaluate ground damage.[29] In case of any major disaster, SUPARCO coordinates with the National Disaster Management Authority (NDMA) and the provincial authorities to provide near-real-time satellite images and analytical reports. As an example, SUPARCO has generated rapid inundation maps and damage estimates of catastrophic floods like the 2010 and 2014 floods and has been updating the flood extent maps regularly during the monsoon season.[30] It is also the point of contact in Pakistan to activate the International Charter on Space and Major Disasters, which allows free access to high-resolution satellite data of other space agencies if a major calamity is declared. This international cooperation was critical in the case of the 2022 super-floods, when cloud-penetrating radar imagery of foreign satellites (e.g., Sentinel-1) was employed together with SUPARCO

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[27] Justin Diehr, Ayorinde Ogunyiola, and Oluwabunmi Dada; A. S. Albahri et al., "A Systematic Review of Trustworthy Artificial Intelligence Applications in Natural Disasters," *Computers and Electrical Engineering* 118 (2024), https://doi.org/10.1016/j.compeleceng.2024.108517; Arief Wibowo et al., "Leveraging Artificial Intelligence in Disaster Management: A Comprehensive Bibliometric Review," *Jàmbá: Journal of Disaster Risk Studies* 17, no. 1 (2025): 1–9, https://doi.org/10.4102/jamba.v17i1.1776; Sheikh Kamran Abid et al., "Toward an Integrated Disaster Management Approach: How Artificial Intelligence Can Boost Disaster Management," *Sustainability* 13, no. 22 (2021), https://doi.org/10.3390/su132212541.

[28] Space and Upper Atmosphere Research Commission (SUPARCO), "Disaster Monitoring and Mitigation," https://suparco.gov.pk/products-services/disaster-monitoring-and-mitigation/#:~:text=SUPARCO%E2%80%99s%20Space%20Application%20Center%20for,SACRED

[29] "Disaster Monitoring and Mitigation: Rehabilitation and Mitigation Support."

[30] Space and Upper Atmosphere Research Commission (SUPARCO), *SUPARCO: Effective use of Space-based information to monitor disasters and its impacts: Lessons Learnt from Floods in Pakistan* (Islamabad: SUPARCO, 2015) https://www.un-spider.org/sites/default/files/150112_SUPARCOBooklet_online.pdf#:~:text=During%20the%20floods%2C%20SUPARCO%20updated,areas%20was%20developed%20on%20the.

data to map one-third of the country submerged under water. The institutional structure of SUPARCO, through SACRED and its status as an UN-SPIDER Regional Support Office, has made the agency the most important source of space-based information in disaster management in Pakistan.

Agreements and specific platforms have been established between SUPARCO and disaster management authorities to coordinate their efforts. SUPARCO collaborates with NDMA and provides space-based information to the NDMA and provincial disaster management agencies at every stage of disaster management, including risk mapping and preparedness, emergency response, and recovery. A notable project is the creation of a NatCat risk modeling system in collaboration with the National Disaster Risk Management Fund (NDRMF). In this project, a geo-referenced exposure and hazard database is being developed to simulate the effects of floods, droughts, cyclones, and other hazards in the current and future climatic conditions.[31] The NatCat model is the first of its kind in the region, which incorporates historical satellite data, climate change projections, and socioeconomic exposure to give granular risk assessments and financial loss estimates at the sub-district level. These initiatives demonstrate an institutional awareness in Pakistan that climate change is increasing the risks of disasters, and that space science (i.e., Earth observation data) should be used to plan long-term resilience. Remarkably, SUPARCO also supports international frameworks; it helps NDMA report for the Sendai Framework 2015-2030 and the Paris Climate Agreement objectives through satellite-based environmental monitoring and hazard mapping.

Space-Based Technologies and Tools Utilized

In managing climate-related disasters, Pakistan uses various space technologies, with a focus on EO satellites and geospatial analytics. One of

[31] Pakistan Delegation to the United Nations, *Statement by Pakistan at the 62nd Session of the Scientific & Technical Subcommittee (STSC) of the Committee on the Peaceful Uses of Outer Space (COPUOS)*, February 2025, https://www.unoosa.org/documents/pdf/copuos/stsc/2025/Statements/3_Pakistan_for_upload.pdf

the greatest achievements was the introduction of indigenous remote-sensing satellites that offer high-resolution imagery to be used domestically. In 2018, SUPARCO launched the Pakistan Remote Sensing Satellite-1 (PRSS-1), which provides ~1 m panchromatic and ~3 m multispectral imagery with a 4-day revisit time, allowing the country to have access to current imagery of its terrain without relying on foreign sources.[32] Applications like land use mapping, agricultural monitoring, environmental observation, and natural disaster management are explicitly assigned to PRSS-1.

In early 2025, Pakistan launched its first fully indigenous Electro-Optical Satellite (PRSC-EO1), further enhancing its Earth observation capability.[33] EO-1 satellite has optical sensors to measure reflected sunlight and thermal radiation emitted, which will be utilized to monitor deforestation and glacier retreat, monitor water resources, and give timely information on floods, landslides, and other calamities. This new satellite is a giant leap towards self-reliance and will significantly improve the capability of Pakistan to respond to natural hazards through the provision of on-demand imagery to support early warning and damage assessment applications. Pakistan also accesses data of international Earth observation systems (MODIS, Sentinel) and commercial providers through the Disaster Charter and other partnerships, to provide coverage even in cases (such as heavy cloud-cover floods) where foreign radar or high-resolution imagery is required. SUPARCO has satellite ground stations in Islamabad and Karachi, which are capable of receiving feeds from various satellites and acquiring images of Pakistan and the region within a short time.[34] This multi-source approach indicates an awareness that space-based observation is an important

[32]Space and Upper Atmosphere Research Commission (SUPARCO), *"PRSS-1,"* https://suparco.gov.pk/major-programmes/projects/prss-1/#:~:text=PRSS,reliant%20in

[33]Jamal Shahid, "Pakistan's First Indigenous Observation Satellite Launched," *Dawn*, February 18, 2025, https://www.dawn.com/news/1885968#:~:text=ISLAMABAD%3A%20The%20Pakistan%20Space%20and,Centre%20in%20China%20on%20Friday

[34]SUPARCO, *Effective Use of Space-Based Information to Monitor Disasters and Its Impacts: Lessons Learnt from Floods in Pakistan* (Islamabad: Space and Upper Atmosphere Research Commission, n.d.), https://www.un spider.org/sites/default/files/150112_SUPARCOBooklet_online.pdf

instrument in the management of climate-induced disasters, i.e., constant satellite observation is deemed as essential to offer forecasting services to avert water-related disasters like floods and droughts, which are currently being performed regularly by SUPARCO.[35]

In addition to the orbiting satellites, Pakistan has also made ground-based remote sensing and GIS tools to convert space data into actionable information. The disaster management teams at SUPARCO employ advanced methods of image analysis (multi-temporal change detection and GIS mapping) to outline flood extents, map vulnerable assets, and assess the effects on agriculture or infrastructure. In case of major floods, SUPARCO updates inundation maps daily, giving district-wise figures of submerged areas and crop losses, which are directly used in relief planning.[36] The agency also has an Integrated Flood Analysis System and multi-hazard vulnerability assessments (floods, earthquakes, cyclones, droughts) based on remote sensing inputs. To share this information, a web-based Disaster Watch portal has been established to enable NDMA and provincial authorities to access near-real-time satellite analysis in times of emergencies.[37]

At the end-user level, the NDMA itself has led the way in incorporating space-based data. NDMA has created the new National Emergencies Operation Center (NEOC) that has real-time satellite feeds and sophisticated analytics to predict disasters three months in advance.[38] NEOC uses an integrated approach that combines GIS, remote sensing,

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[35] Suhaib Bin Farhan, *Space Technology to Combat Global Climate Change* (Islamabad: Center for International Strategic Studies, 2022), https://ciss.org.pk/PDFs/Space-Technology-to-Combat-Global-Climate-Change.pdf#:~:text=One%20of%20the%20most%20important,measuring%20sea%20levels%2C%20glacier%20mass

[36] *Effective Use of Space-Based Information To Monitor Disasters and its Impacts.*

[37] "Disaster Monitoring and Mitigation: Rehabilitation and Mitigation Support," https://suparco.gov.pk/products-services/disaster-monitoring-and-mitigation/https://suparco.gov.pk/products-services/disaster-monitoring-and-mitigation/

[38] National Disaster Management Authority (NDMA), "National Emergencies Operation Centre (NEOC)," https://www.ndma.gov.pk/neoc#:~:text=Equipped%20with%20the%20latest%20tools,By%20analyzing

climatology, meteorology, hydrology, and data science information to monitor changing hazards and climate anomalies to allow a proactive approach to disaster risk. In addition, NDMA also installed an electronic Multi-Hazard Vulnerability and Risk Assessment (e-MHVRA) system, which uses remote sensing images to conduct dynamic risk mapping. The platform enables real-time data entry and hazard mapping, facilitating evidence-based contingency planning and more rapid dynamic response to the emerging threat. Such utilization of geospatial tools implies that Pakistan is no longer just amassing satellite data, but it is actively using it, like mapping of flood plains, monitoring of glacier lakes, drought risk zoning, and analysis of landslide susceptibility to update disaster management strategies.

There is a growing interest in leveraging AI and ML to complement these abilities, including automating the process of classifying satellite images to identify damage quickly and making use of AI models to better predict flooding. Although in the early phase, Pakistani scientists have started exploring the flood mapping and prediction of forest fires by satellite-generated data driven by AI.[39] Pakistan communication satellites (PakSat-1R launched in 2011) also offer auxiliary support as they allow broadband and telecommunication services to remote or disaster-affected regions.[40]

Policy Frameworks and National Strategies

Pakistan's commitment to utilizing space science for disaster risk reduction is reinforced at the policy level. In 2023, the government endorsed a detailed National Space Policy, developed by SUPARCO, that clearly states the need to use space technology to address socio-economic issues such as natural calamities and climate risks.[41] The vision of the policy is to incorporate

[39]GSMA, *Combatting Forest Fires with AI: Pakistan Case Study*, May 2024, https://www.gsma.com/solutions-and-impact/connectivity-for-good/mobile-for-development/wp-content/uploads/2024/05/GSMA_CombattingForestFiresWithAI_Pakistan_Web-1-1.pdf
[40] *Statement by Pakistan at the 62nd Session of the Scientific & Technical Subcommittee (STSC) of the Committee on the Peaceful Uses of Outer Space (COPUOS),* https://www.unoosa.org/documents/pdf/copuos/stsc/2025/Statements/7_Pakistan.pdf
[41]New Space Economy, "Pakistan's National Space Policy: A Roadmap to the Stars," March 1, 2025, https://newspaceeconomy.ca/2025/03/01/pakistans-national-space-policy-a-roadmap-to-the-

space applications into daily life and development planning, emphasizing the application of satellite data in enhancing agriculture, urban planning, and disaster management, as well as the self-reliance of the country in space capabilities. It is worth noting that disaster risk management is a significant area of focus in the policy. It requires the creation of EWS for floods and droughts, mapping hazards with the help of EO, and leading post-disaster recovery with the help of satellite assessment. This is in line with national climate adaptation plans and the Sendai Framework, which represents a strategic realization that space-based data is essential to developing climate resilience. The Space Policy also focuses on international collaboration (e.g., data sharing, satellite missions' collaboration) and human resource development so that Pakistan remains abreast of international best practices in space-enabled disaster management. In addition to the space-specific policy, the place of technology in the overall disaster management and climate change strategies of Pakistan is also recognized. The National Disaster Management Plan (NDMP) 2015-2030 and the National Disaster Risk Reduction Policy promote remote sensing and GIS in hazard assessment and the modernization of early warning infrastructure (flood forecasting models and drought monitoring) in collaboration with technical agencies such as SUPARCO.

Likewise, the climate change policy of the country - the National Climate Change Policy and Climate Change Act - highlights the importance of scientific data and risk mapping to guide adaptation strategies, which in turn implicitly depends on satellite-based measurements of changing environmental patterns (glacial melt, sea-level rise along the coast, land cover changes, etc.). Such policy guidelines are realized in the form of projects such as the NatCat risk model and the working Memorandum of Understanding (MoU) between SUPARCO and NDMA. The NDMA has formalized space data integration into its Standard Operating Procedures (SOPs), e.g., the official NDMA NEOC Projections now incorporate satellite-monitored climate indices to predict seasonal hazard outlooks, and

stars/#:~:text=Pakistan%E2%80%99s%20National%20Space%20Policy%20represents,article%20breaks%20down%20the%20policy%E2%80%99s situation reports during disasters regularly include satellite imagery analysis (maps of flooded areas). This policy and practice convergence shows that Pakistan acknowledges space technology as a strategic resource in disaster risk reduction. More importantly, the government proposed a large increase in funding for SUPARCO, with an 850 percent increase in development funding in 2024-2025, in part to increase satellite infrastructure and "develop space technology capabilities" to serve national requirements such as disaster management.[42] Such an investment supported by the policy implies a willingness to fill historical gaps and a desire to ensure that space-based tools are used systematically to protect communities against climate-related disasters.

Leveraging Space Technologies: Challenges and Way Forward

Although there is a visible improvement, there are still major obstacles that hinder the effective utilization of space science in managing climate disasters in Pakistan. The absence of domestic launch capability and limited satellite assets is one of the significant gaps. Pakistan has not yet developed its satellite launch vehicle (rocket) to place satellites in orbit, and it depends on foreign launches (mainly through China) to place its satellites in orbit. Such reliance may limit the ability to rapidly grow the EO infrastructure and expose the most important missions to the whims of other schedules and geopolitical factors. The existing EO constellation of the country is also limited, with three functioning optical satellites (PRSS-1, PakTES-1A, and PRSC-EO1) and no SAR satellites, which implies a lack of all-weather imaging. In cloudy monsoon conditions, Pakistan resorts to foreign SAR data (European Sentinel-1 or commercial providers) to map flood inundation.

The integration of data sources and agencies is still an improvement point, although platforms such as e-MHVRA are a step in the right direction, there

[42] 4 News HD, "Federal Budget Proposes 850 Percent Increase in SUPARCO Development Budget," June 10, 2024, https://24newshd.tv/10-Jun-2024/federal-budget-proposes-850-percent-increase-in-suparco-development-budget#:~:text=Federal%20budget%20proposes%20850,significant%20rise%20from%20the

is still fragmentation between meteorological data (Pakistan Meteorological Department), hydrological data (river flow sensors), and satellite imagery analysis (by SUPARCO). There is a continuing challenge to create a single, interoperable data system of early warning, a system that integrates space-based data with ground sensor networks and socio-economic data. Resource limitation, in terms of finance and infrastructure, is another challenge. The budget of SUPARCO was not very large in the recent past, which limited ambitious projects. The general performance of the space agency in its 50+ years has been termed as a snail's pace, mainly due to the lack of steady funding. To illustrate, when the neighboring nations were busy investing in space-based crop monitoring and climate observation satellites, the programs in Pakistan were sometimes stagnated due to funding cutoffs and sanctions (during the 1990s, international embargoes restricted the use of advanced technology, slowing down the development of satellite projects). The influx of new funds in 2024-2025 is a positive development; however, the effective use of these funds will be critical.

Infrastructural constraints like the lack of domestic image processing and distribution network at local scales also exist - many end-users in provincial disaster management or local planning departments remain untrained or lack the tools to access satellite-derived products on their own. It implies that SUPARCO and NDMA produce useful data, but the uptake of the last-mile into the district-level disaster preparedness or climate adaptation planning may be slow or inconsistent. This gap will have to be bridged through capacity-building and decentralization of some of the geospatial capabilities to provincial units. Also, inter-agency coordination can be enhanced further to achieve effective early warning. It is important to have climate scientists, meteorologists, and satellite remote sensing analysts working together, such as combining climate models and satellite monitoring of glaciers and weather patterns.

Conclusion

The rising number and severity of climate-related catastrophes in Pakistan point to the necessity of an effective disaster management system that is technology-driven. This paper has established that space science and technology, especially EO, GIS, and SRS, have become an essential component in disaster preparedness, response, and recovery. Although nations such as China, Japan, and the US have managed to institutionalize such technologies, Pakistan has done well in this regard through its national space agency, SUPARCO. Moreover, SACRED, NatCat Risk Model, and Disaster Watch portal are the initiatives that demonstrate the increased use of space-based solutions in Pakistan to enhance risk assessment, early warning capabilities, and situational awareness in emergencies.

However, several systemic loopholes still exist. Pakistan has no indigenous satellite launch capability, a small constellation of EO satellites, and still relies on foreign partners to provide it with essential imaging, particularly in poor weather conditions. Also, the complete operationalization of space-based data into subnational and local disaster management systems is not fully consistent, and it is frequently constrained by infrastructural, technical, and institutional shortcomings. In addition, despite the recent progress in policy, such as the National Space Policy (2023) and the increment of development funding to SUPARCO, a renewed national interest is evident, but the successful implementation of the policy needs long-term inter-agency coordination, investment, and capacity building across all administrative levels.

To realize the full potential of space technologies, Pakistan needs to institutionalize a multisectoral approach of fusing scientific innovation with inclusive governance. This involves the development of synergies among space scientists, climate modelers, and disaster response practitioners; the strengthening of regional and international collaboration; and the decentralization of space-derived information to be used in making community-level decisions timely manner. Finally, a sustainable future of Pakistan is not only about the technological progress but also the political determination to integrate space science in the national development and disaster risk reduction plans.