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Article

From Mountains to Data: Low-Cost Weather Stations in Kyrgyzstan's Challenging Terrain

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Abstract: Kyrgyzstan, a landlocked nation in Central Asia, is characterized by its rugged mountainous terrain, which covers approximately 90% of its land area. This unique geography poses specific challenges related to climate vulnerability. To address these challenges, we propose a comprehensive approach that involves gathering meteorological data and making it accessible to decision-makers. By leveraging LoRaWAN communication technology, which efficiently transmits sparse and low-speed data over long distances while minimizing power consumption, we can enhance climate resilience. The Internet Society Kyrgyz Chapter, in collaboration with the International Centre for Theoretical Physics (ICTP) and the Central Asia Institute for Applied Geosciences (CAIAG), has initiated the installation of meteorological sensors and disaster mitigation devices, including river water level sensors, terrain moisture sensors, and tilt detectors. These sensors collect critical data, which is stored within the country on an ad hoc server. Stakeholders can access this data according to their specific requirements. This paper outlines the criteria for selecting the deployed equipment and provides details on the installation process at pilot sites, along with the challenges encountered during project execution.

Keywords: Kyrgyzstan; Internet of Things; weather stations; LoRa; LoRaWAN

1. Low-Cost Weather Stations

Low-cost, low-power, and long-range weather stations have seen advancements in recent research. These stations offer a cost-effective solution for monitoring weather conditions both in developed and developing countries. The use of technologies such as LoRa wireless networking for the Internet of Things (IoT) has enabled the development of weather stations that can cover large areas while consuming minimal power. These stations are equipped with various sensors to monitor parameters such as temperature, humidity, air pressure, wind and rain amount. The collected data can be stored in cloud servers and accessed remotely. The implementation of these weather stations aim to adhere to the standards set by organizations like the World Meteorological Organization (WMO) [1]. The relevance of these advancements lies in their ability to provide accurate weather predictions, which can have significant impacts on sectors such as disasters mitigation, agriculture, hydroelectric powering and tourism. Additionally, the low-cost nature of these stations makes them more accessible and affordable for deployment in developing countries where resources for such technologies are limited.

As an example of new development, the integration of satellite downlink signal attenuation measurement for real-time rain rate evaluation presents an interesting aspect compared to other consolidated precipitation measurement instruments [2]. This system, endorsed by leading satellite operators and weather forecast market players, showcases the potential for developing new services based on project results, highlighting the exponential growth in the business related to weather data.

Additionally, the use of city buses as mobile weather stations for real-time weather monitoring and prediction demonstrates an innovative approach to achieving a better balance of coverage than static observatories [3]. The system utilizes local information processing and bus mobility to monitor minute details and weather changes within a specific area, delivering highly detailed weather information and updates at short intervals, leveraging artificial intelligence techniques.

Lastly, the development of collaborative approaches for agricultural development, such as low-cost weather stations for climate-smart agriculture, emphasizes the importance of such technologies in enhancing agricultural productivity and sustainability in developing countries [4,5]. These systems offer affordable, accessible, and real-time monitoring capabilities that are vital for mitigating climate change impacts and promoting sustainability.

In conclusion, the current advancements in low-cost, low-power, and long-range weather stations are highly relevant for developing countries and emerging economies. They offer innovative solutions for environmental monitoring, agricultural development, and climate change mitigation, providing critical support for informed decision-making and sustainability efforts in resource-constrained settings.

2. Kyrgyzstan

Kyrgyzstan, also known as the Kyrgyz Republic, is a sovereign state in Central Asia. It is renowned for its stunning natural landscapes, predominantly consisting of mountain ranges like the Tian Shan and Pamir. The nation's capital and largest city is Bishkek, which serves as the administrative and economic hub. With a population estimated at around 7.25 million in 2024, Kyrgyzstan is home to a diverse array of ethnic groups, with the Kyrgyz people making up the majority. The country's official languages are Kyrgyz and Russian, reflecting its rich history and cultural richness. Economically, Kyrgyzstan has a mixed performance. Its Gross Domestic Product (GDP) was estimated at \$13.758 billion in 2024, with a per capita income of around \$2,000. The economy relies heavily on agriculture, mining (especially gold), and remittances from citizens working abroad. Despite low income levels and economic challenges, Kyrgyzstan has a relatively low Gini coefficient, indicating a more equitable distribution of income compared to many other countries. Kyrgyzstan's history is marked by its position along the Silk Road and its succession under various empires and powers. Today, it is a unitary presidential republic, having declared independence from the Soviet Union in 1991. The country continues to navigate its path towards economic stability and growth, leveraging its natural resources and strategic location.

2.1. Geography and Climate Change

Kyrgyzstan boasts a diverse geography primarily characterized by its rugged mountainous terrain, which encompasses approximately 90% of its land area. The country is defined by the imposing presence of the Tien Shan range, which traverses its territory from east to west. This mountain system is renowned for its majestic peaks, including Peak Pobeda, standing at 7,439 meters, and Khan Tengri, reaching 7,010 meters above sea level. The Tien Shan range not only serves as a geographical hallmark but also influences various aspects of Kyrgyzstan's environment and society. Around 90% of Kyrgyzstan's electricity generation comes from hydropower. Figure 1 shows the country's topography. Its towering summits contribute significantly to the nation's climatic diversity, acting as a barrier to moisture-laden air masses, thereby influencing precipitation patterns across the region. Moreover, the mountains serve as reservoirs for glacial meltwater, crucial for sustaining downstream ecosystems and supporting agricultural activities in the fertile valleys below. Beyond their environmental significance, the mountains of Kyrgyzstan also hold cultural and historical importance, serving as a backdrop to nomadic traditions and ancient trade routes that have crisscrossed the region for centuries. Despite the challenges posed by the rugged topography, such as limited arable land and difficult access to remote areas, the mountains also offer opportunities for tourism, particularly in the realm of ecotourism and adventure sports like mountaineering, trekking, mountain biking and skiing. Thus, while the mountains of Kyrgyzstan present both obstacles and opportunities, they remain central to the country's identity, shaping its landscape, culture, and socio-economic development. Among the countries in Eastern Europe and Central Asia, Kyrgyzstan is the third most vulnerable to the effects of climate change [6,7]. The average temperature has increased from 5.8 °C to 6 °C in the last 20 years. In 2013 the

World Bank estimated a likely increase of 2 °C in average mean temperature by 2060 and of 4-5 °C by 2100, noting that the country’s glaciers were significantly reduced and projected to decline further.



Figure 1. A map showing Kyrgyzstan topography. Credit: www.grida.no/resources/5327

2.2. Telecommunications Infrastructure

Kyrgyzstan’s telecommunications infrastructure reflects the country’s efforts to modernize and expand connectivity in recent years. The sector is primarily overseen by the Ministry of Digital Development, which regulates telecommunications policies and fosters industry growth. Kyrgyzstan has made significant strides in expanding its telecommunications network, with widespread coverage of mobile and Internet services across urban and rural areas. Mobile penetration rates are relatively high, driven by competition among several major operators offering 3G and 4G services. Mobile penetration rates have plateaued at around 140% in terms of population, indicating saturation in the market. Nevertheless, rural areas with low population density are not served [8], as can be observed in Figure 2.



Figure 2. Cellular network coverage in Kyrgyzstan (areas in pink color) showing that rural areas with low population density and remote areas are not served.

The country has also witnessed increasing adoption of broadband Internet, facilitated by investments in fiber-optic infrastructure and satellite connectivity. Approximately 1.9 million people in Kyrgyzstan use the Internet, a number expected to grow. Despite these advancements, challenges

persist, including the need for further investment in rural connectivity, ensuring affordable access for underserved populations, and addressing cybersecurity concerns. Looking ahead, the government's focus on digitalization and e-governance initiatives underscores the importance of continued investment in telecom infrastructure to support economic growth and social development in Kyrgyzstan.

2.3. Central Asia Institute of Applied Geosciences (CAIAG)

The Central Asian Institute of Applied Geosciences (CAIAG) [9], an independent non-profit organization, was established in 2002 through a cooperative agreement between the Government of the Kyrgyz Republic and the German GeoForschungs Zentrum in Potsdam, Germany. CAIAG's mission revolves around applied geoscience research, environmental monitoring, and sustainable resource management. The research focus of CAIAG includes the management of dedicated monitoring networks for seismology, geodesy, and hydro-meteorology, installation of high mountain observatories that provide critical data on glacial dynamics and water resources and the maintenance of observational data that are managed within a Geodata Information System, including a geodatabase and web interfaces for open access.

3. Proposed Architecture

LoRaWAN (Long Range Wide Area Network) is a communication protocol designed for low-power, long-range wireless connectivity. It enables devices to communicate with Internet-connected applications over extended distances. LoRaWAN networks follow a star-of-stars topology, where End Devices (EN) communicate with nearby Gateways, which connect to a Network Server. Energy consumption is minimized since the end device only wakes up when it needs to send data; after each transmission two short receive windows are established during which the end device can receive downlink commands and then returns to sleep. Messages are detected by all gateways within range, ensuring robust coverage.

The key components in the standard LoRaWAN architecture are:

- **End Devices:** these are the sensors equipped modules deployed in the field. They collect data and communicate wirelessly using LoRa modulation. Examples of end devices include temperature sensors, humidity monitors, and air quality monitoring devices. End devices are usually battery-operated and are essential for gathering information from the physical environment.
- **Gateways:** they act as intermediaries between end devices and the network server. Their primary role is to receive messages from end devices and forward them to the network server. Gateways are connected to the network server via various backhaul options, such as cellular (3G/4G/5G), Wi-Fi, Ethernet or satellite links, so they perform the protocol conversion from LoRaWAN to IP. Outdoor enabled Gateways provide larger coverage and are suitable for both rural and urban areas. They are usually mounted on cellular towers, rooftops, or tall structures and are equipped with external antennas.
- **Network Server:** manages the entire LoRaWAN network. It receives messages from gateways, performs message deduplication (keeping a single copy of duplicate messages if two or more gateways receive the same message from an end device), and handles device authentication and security. It forwards the end node's payload to the specified Application server. The network server is a critical piece of software running on a server infrastructure and it also interacts with the Join and Authentication Servers to allow only authorized access to the infrastructure.
- **Application Servers:** they process application-specific data securely, applying the required keys to decode the payload and make it available to the authorized users only. The Application servers play a crucial role in extracting meaningful insights from the collected data. They are also able to transmit downlink commands and acknowledgments all the way through the chain to configure specified nodes, since all the communications are bidirectional, although uplink traffic constitutes the highest load.

Figure 3 shows on the left a Standard LoRaWAN architecture, where the End Nodes send sensor’s data to a Gateway that is connected via TCP/IP to a Network Server. The Application Server decrypts the specific data stream thus preserving the privacy from other applications handled by the Network Server. On the right the proposed architecture in which all the servers and the gateway are integrated in a disruption tolerant gateway (DTG).

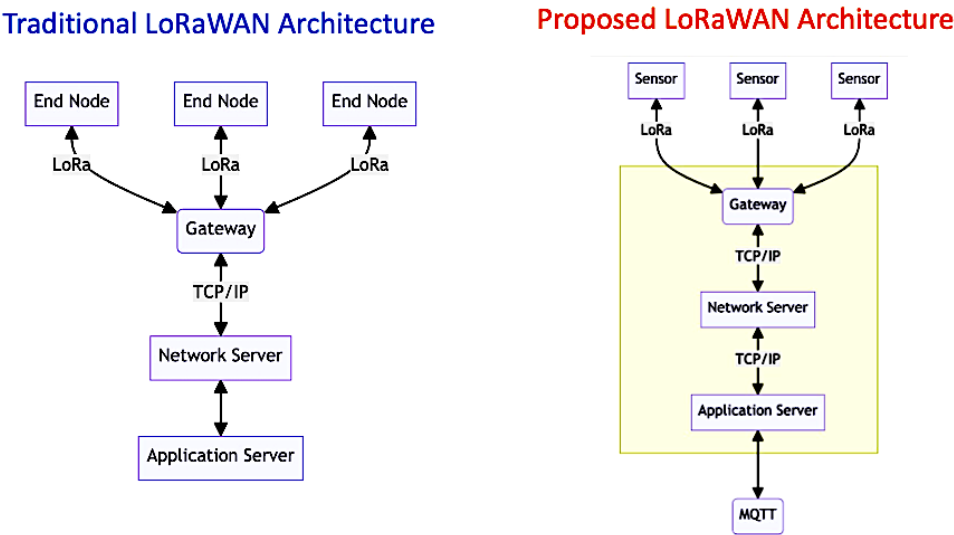


Figure 3. Comparison of the standard LoRaWAN architecture with the proposed solution that integrates the various servers and the gateway in the same box, adding disruption tolerance.

3.1. DTG: Disruption Tolerant Gateway

In the context of deploying LoRaWAN networks in extreme and rural environments, a significant challenge arises due to the intermittent availability of cellular networks in remote areas. These networks often experience prolonged outages, primarily because they rely on diesel generators for power, which can be unreliable. Furthermore, fuel supply in remote areas poses additional challenges. To address this issue, gateways must be equipped with local data storage capabilities. When the cellular service becomes operational again, the gateway should automatically transmit the stored data to prevent any gaps or discontinuities in the records. The key component of our proposed LoRaWAN architecture is a Disruption Tolerant Gateway, able to address the following possible causes of disruption:

- 1. Lack of power at the Gateway
- 2. Lack of power at the cellular Base Station
- 3. Coverage issues of the cellular Base Station for end nodes

Item 1 can be addressed by installing a photovoltaic system with a suitable solar panel and battery even if the system is connected to the grid, to prevent power losses. Item 2 can be addressed by storing data in a local buffer to send them when the Base Station becomes again available. For Item 3, while the gateway must have Internet connectivity, and therefore must be within the cellular service coverage area or have satellite connectivity, the sensors need only to be within the coverage area of the gateway, which under line of sight conditions can be dozens of kilometers. So there is no need for the sensors to be under Cellular coverage.

The right side of Figure 3 depicts the proposed solution, where the DTG includes a LoRaWAN gateway as well as all the required Network and Application servers.

We first developed a prototype that used a dual SIM cellular modem, a Raspberry Pi with local storage in a micro SD card and concentrator module (the radio part of a gateway). The prototype

worked well as a proof of concept, but it required a significant amount of customization, hampering its usefulness for a large scale implementation in remote areas. Looking at the commercially available LoRaWAN gateways, we found that the Milesight UG67 [10] fits most of our requirements. It has 8 GB of flash for local data storage and supports the MQTT protocol which addresses the disruption of communication with the cellular base station. It also has internal Network, Application, Join and Authentication servers so it is a very complete solution. The only shortcoming with respect to our prototype is that the cellular modem does not support dual SIM. UG67 is a robust 8-channel outdoor LoRaWAN gateway that supports connection with more than 2000 nodes. It has an IP67 (Ingress Protection) waterproof case making it a suitable solution for remote environments. The Ethernet interface can also be used to connect to a satellite modem in cases in which no terrestrial connectivity is available. It can be powered at 12 volt through a weather protected connector facilitating its connection to a photovoltaic system. We therefore decided to use the UG67 for the field deployment in Kyrgyzstan.

4. Other Gateways

There are a number of vendors that offer LoRaWAN gateways, the ones useful to collect environmental data in extreme climates should meet the following criteria:

- Weather resistant, with a wide temperature range
- Support for simultaneous reception of at least 8 frequencies in the locally available band
- Low energy consumption, capability of being powered through a weatherproof 12 volt connector for easy interfacing with photovoltaic system
- Waterproof connector for external LoRa antenna, required for long range coverage
- Fitted with Cellular modem (3G and 4G), preferably with external antenna
- Internal data storage with automatic resumption of cellular data transmission after an interruption
- Built in internal Authentication, Join and Network servers
- Support for MQTT protocol

Commercially available devices meeting these requirement include:

4.1. SenseCAP Outdoor Gateway—LoRaWAN EU 868 MHz

This device [11] has a built in server that provides the required LoRaWAN servers with MQTT support. The IP66 enclosure makes it weather resistant over the -40 °C to 70 °C temperature range, offers 8 GB eMMC memory, supports a wide number of 4G bands with an SMA connector for external antenna. It has an internal LoRa antenna and also supports an external one. The receiver sensitivity is -139.5 dBm. Consumes 3.6 W at 12 V, supplied through a weatherproof connector. The CPU is the TI AM3358 Cortex-A8 running at 1 GHz

4.2. Heltec HT-M02 (V2)

This IP66 all aluminum case gateway [12] has an operating temperature from -40 °C to 85 °C, uses the new SX1303 chip, which has better sensitivity than the SX1301 and improved positioning capabilities. It has a 4G modem (Cat. 1 and Cat. 4) and can be powered from 4.5 to 17 volts.

It can connect to various network servers such as TTN and Chirpstack.

4.3. RAK 7289CV2

This recently introduced gateway [13] has an LTE modem and a built in WiFi Access point for configuration. It has a Chirpstack server that implements all the requirements for a private LoRaWAN network with MQTT support. It buffers LoRa frames in Packet Forwarder mode to prevent data loss. It offers optional support for the Listen Before Talk (LBT) protocol, which allows a relaxed duty cycle of 10% instead of the normal 1%. The IP 67 enclosure houses the LTE, Wi-Fi, and GPS antennas, which means that the installation of the gateway must take into account the direction of the closest Cellular tower. Operating temperature is from -30 °C to +55 °C. The LoRa antenna is external, so it can be omnidirectional. It has cable glands for the 12 volt supply.

4.4. Browan Outdoor Micro Gateway V2

This model [14] can receive up to 16 concurrent channels, and has connectors for external antennas (LoRa, 3G/4G and GPS). There is no Wi-Fi. The Ethernet port supports 10/100/1000 Mbps and can be used to power the device, as an alternative to 12 V DC used in conjunction with solar power. IP68 ingress protection, with a temperature range from -20 °C to 60 °C (optional for -40 °C 60 °C). It offers a LoRaWAN network server embedded and supports downlink LBT as well as MQTT. Supports dual SIM cards and has multiple watchdogs for system monitoring.

4.5. Mikrotik Knot LR8

An IoT LoRa Gateway that uses both Narrow Band and CAT-M technologies. Does not support legacy 3G and 4G. Tested at temperatures from -40°C to 70°C. Maximum power consumption is 23 W. Supports Bluetooth version 5.2. It is not weatherproof but it could be housed in weatherproof box. It must be connected to an external network server [15].

4.6. Iridium Urb-IoT Outdoor

This is a LoRa Gateway [16] that can also connect to the Iridium Satellite network, besides cellular, Bluetooth and WiFi, so it can be deployed in places lacking Cellular coverage. Supports both LTE-M and NB-IoT. Rated IP 68, does not have external antennas. It handles data locally to reduce data transmission and cloud processing. The temperature range is from -40 to +70 °C. The 20100 mAh battery can lasts up to 72 hr, and the gateway can be powered through a USB-C IP68 connector at voltages from 5.4 to 13.5 V. It supports GPS, GLONASS, Beidou and Galileo. There are recurring charges for the service which are handled by local partners.

4.7. Concluding Considerations

We have presented some of the available gateways that satisfy at least part of the requirements of our project. The final choice was guided by the following considerations:

The SenseCAP meets all our requirements, and it is a good alternative, but has less memory and therefore less resiliency regarding the loss of cellular connectivity.

The Heltec has very good gateway features, but does not have the internal servers needed for DTG capabilities.

The Rak7289 is a very good new contender but we have had no opportunity to test it.

The Browan V2 is a newer version of a gateway that we have tested in the past, which had no server capabilities. We plan to test this model which, compared with the Milesight, has the advantage of dual SIM support and external 3G/4G antenna.

The Mikrotik Knot is power hungry and does not have internal servers or weather resistant capabilities.

The Iridium is very convenient for places outside the cellular coverage, but requires monthly extra payments for the satellite service and there are no Kyrgyzstan partners listed in their website.

5. LoRaWAN Equipped Sensors

A number of sensors are being offered with a LoRaWAN transceiver attached so that they can be configured to automatically transmit the collected data to any gateway on range for further forwarding to the selected servers. Additionally, most sensors can be connected to a LoRaWAN transceiver module using standard interconnection buses.

5.1. Barani Weather Station

As for the weather station we opted for the MeteoHelix IoT PRO from Barani Design technologies¹. It is a micro-weather station based on new IoT wireless technologies and sensors. Featuring a patented helical design enclosure, it can meet quality standards for climatic observations as set by the World Meteorological Organization (WMO) without using any power consuming fan. It measures temperature, humidity, atmospheric pressure, and solar irradiation, from which dew and frost points are derived with good accuracy levels. The MeteoHelix IoT PRO has a small solar panel that charges an internal Li Ion battery that allows over 3 months of operation without sun. We also deployed the stand-alone MeteoWind IoT Pro wind sensor and the MeteoRain 200 Compact sensor, which have their own LoRaWAN transceivers and meet quality standards as defined by WMO.

5.2. Additional LoRaWAN Equipped Sensors

Statistics from the Centre for Research on Epidemiology of Disasters (CRED) (Brussels, Belgium) show that landslides are responsible for at least 17% of all fatalities from natural hazards worldwide [17],[18]. The recent disaster in Papua New Guinea [19] is a striking example of great human loss.

For land slides mitigation purposes, it is also necessary to install soil moisture and temperature sensors, buried at certain depths, as well as tilt sensors above the ground. The latter measure the angle between the instrument body and the plumb line in two horizontally perpendicular directions. We chose the SenseCAP S2105 from SEEED Studio for moisture and temperature measurement [20] and the Milesight - EM310-TILT [21] for inclination angle measurement, since they are already equipped with LoRaWAN transceivers.

Figure 4 shows the location of the soil moisture and temperature in the Tatyr site. Sample of the daily inclination readings is presented in Figure 5. Similar deployments were made in other landslide prone areas.

¹ <https://www.baranidesign.com/meteohelix-pro-weather-station>

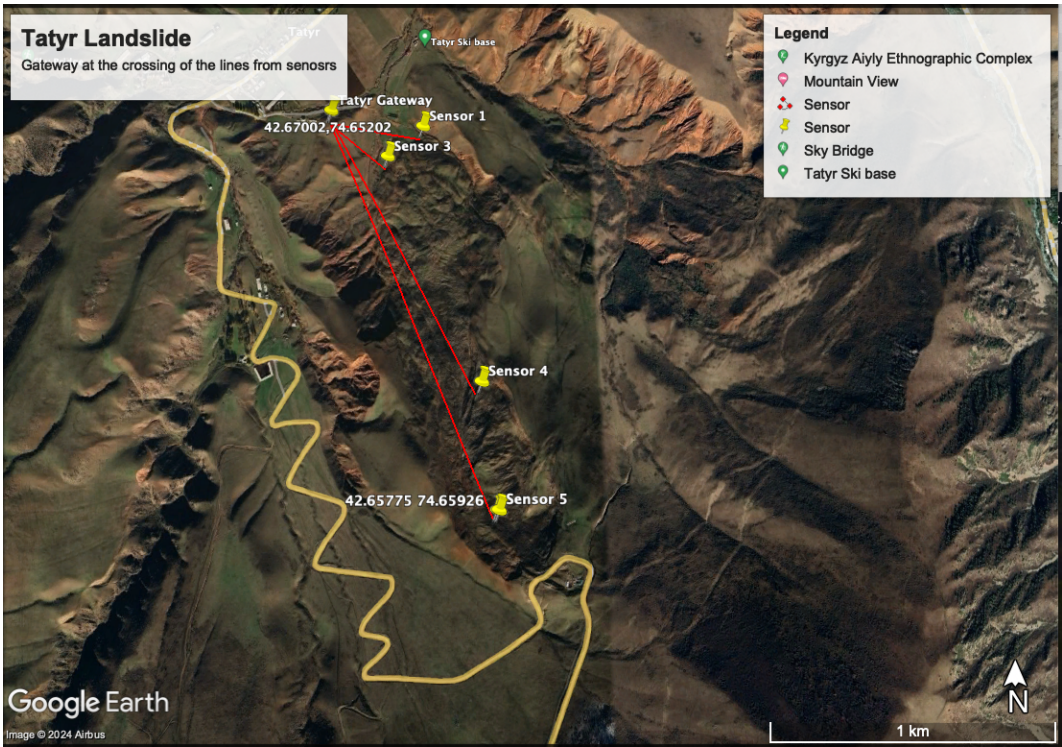


Figure 4. LoRaWAN equipped soil moisture and temperature sensors send data to the DTG gateway in the Tatyr site

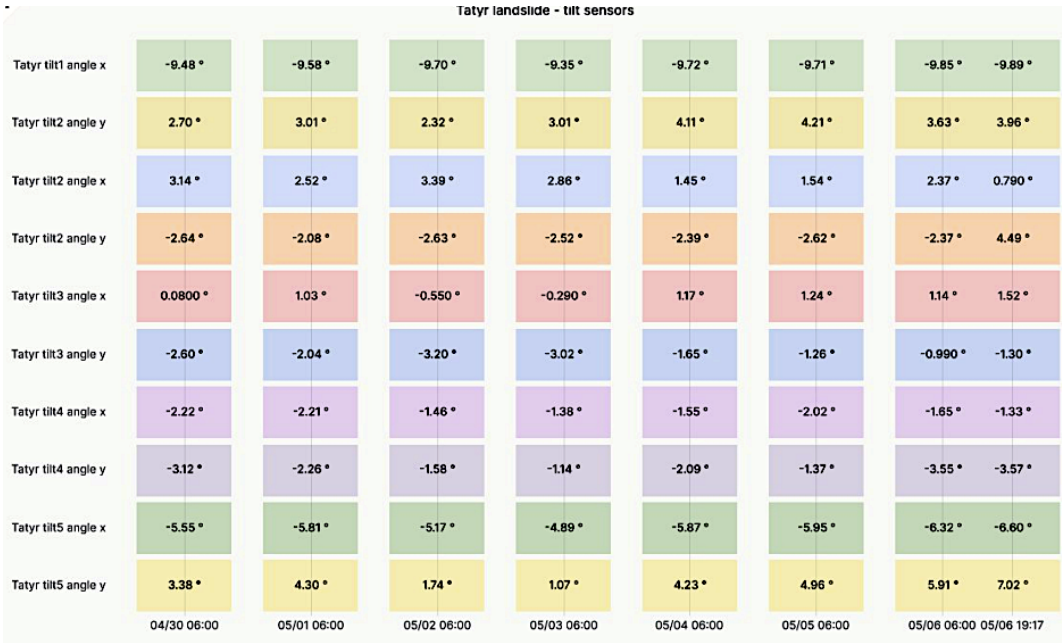


Figure 5. Angular displacement recorded by the tilt sensors in the Tatyr site.

Besides periodic transmissions, the tilt sensors can be programmed to send a message whenever a given angle threshold is surpassed.

Regarding flood prevention, measuring the water level in upstream rivers is of paramount importance. We therefore installed an ultrasonic distance meter in a bridge, the Milesight EM310-TILT. Subtracting the current distance measurement from the maximum reading ever captured provides an indication of the river water level. Turbulence can cause erratic readings, so data filtering is required to eliminate outliers.

6. Software Tools

6.1. MQTT Protocol

The MQTT protocol has emerged as a prominent communication standard for the Internet of Things (IoT) and other resource-constrained environments. Its lightweight design, efficient message exchange, and publish-subscribe model make it well-suited for scenarios where low bandwidth, limited processing power, and intermittent connectivity prevail.

The MQTT protocol is a client-server messaging protocol designed to facilitate efficient communication between devices in distributed systems. It operates over TCP/IP or other transport protocols, providing a lightweight and reliable mechanism for exchanging messages. The central tenet of MQTT lies in its publish-subscribe paradigm, where clients (both publishers and subscribers) interact with a central broker. MQTT employs a topic-based publish-subscribe model, allowing publishers to disseminate information to multiple subscribers interested in specific topics. Publishers send messages to a broker, which then forwards them to relevant subscribers based on their specific interest. This decoupling of publishers and subscribers enables scalable and flexible communication. MQTT offers three levels of QoS:

- QoS 0 (At most once): The broker delivers the message once without any acknowledgment. No retries occur.
- QoS 1 (At least once): The broker ensures that the message reaches the subscriber at least once. Retransmissions occur until acknowledgment is received.
- QoS 2 (Exactly once): The most reliable level, where both publisher and subscriber engage in a handshake to guarantee exactly-once delivery.

The choice of QoS level depends on the application's requirements and network conditions. As we cannot rely on a stable connection in rural areas, we decided to opt for QoS 2 in our DTG. MQTT is particularly well-suited for low-bandwidth networks and battery-powered sensors. MQTT supports authentication and encryption mechanisms.

6.2. Telegraf, Influx and Grafana

The TIG stack, comprising Telegraf, InfluxDB, and Grafana, represents a set of open-source tools tailored for efficient collection, storage, visualization, and alerting of system metrics. This stack finds widespread adoption in IoT. Telegraf, an integral part of the TIG stack serves as a versatile agent responsible for gathering and aggregating data from various sources including MQTT. Telegraf boasts a modular design, allowing seamless integration with diverse systems, databases, and devices. Metrics are pushed to InfluxDB, the designated data store. InfluxDB serves as the repository for time-series data ingested by Telegraf. It excels in handling high-frequency writes, making it ideal for real-time data streams. Users define retention policies to manage data retention duration. Historical data can be pruned or downsampled based on policies. InfluxQL enables SQL-Like Query Language for data retrieval. Grafana complements the stack by providing a modern, customizable dashboarding solution. It offers a rich array of visualizations (line charts, heatmaps, gauges) and panels (graphs, tables, alerts), as shown on Figure 6 for the case of Kyrgyzstan, and users can create dynamic dashboards by combining multiple panels. Grafana seamlessly integrates with InfluxDB as a data source. Grafana supports alert rules based on thresholds or anomalies.

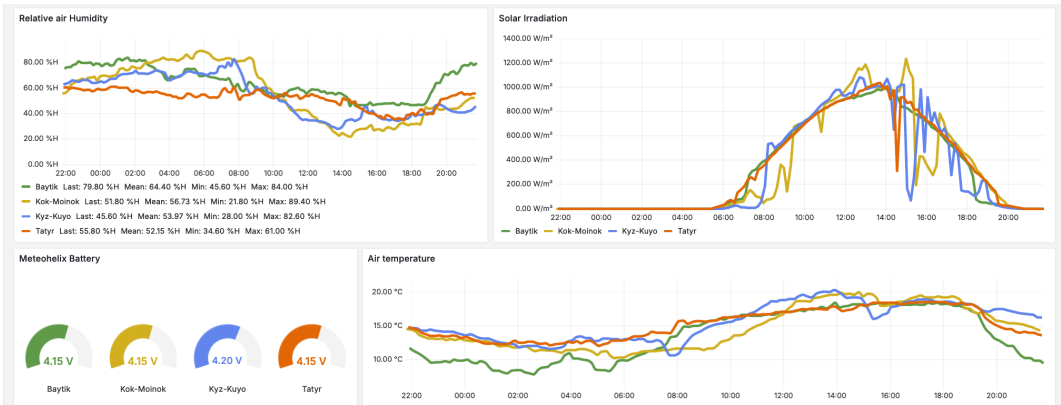


Figure 6. Home dashboard of the Grafana tool showing relative humidity, irradiance, battery voltage and air temperature for the Baitik, Kok-Moinok, and Kyz-Kuio sites on June 4, 2024.

6.3. OpenVPN

To be able to connect to the gateway remotely we deployed Open VPN. OpenVPN is an open-source virtual private network (VPN) solution that stands as a robust and widely adopted protocol for secure communication over untrusted networks. It offers a flexible and extensible framework for creating encrypted tunnels between devices, ensuring confidentiality, integrity, and authenticity of transmitted data. Each IoT gateway connects using its specific encryption method, and access to services is secured through encrypted login credentials. By using an OpenVPN server hosted at ISOC Kyrgyz Chapter, we are able to remotely connect to the gateways to perform maintenance, updates and to add new devices. A Virtual Private Network (VPN) server has been established to facilitate internal communication with LoRaWAN gateways within an Alma Linux environment. AlmaLinux OS, an open-source operating system, underpins the server’s environment. Connectivity to the machine, both for SSH access and maintenance purposes, is maintained via its designated IP address. Within this network, four gateways are connected through the tunnel subnet provided by the VPN. Additionally, the server interfaces with the external network through Network Address Translation (NAT).

7. Deployments in Kyrgyzstan

As part of an ISOC Foundation-funded project, the Internet Society Kyrgyz Chapter and the ICTP deployed four pilot systems, including four gateways, four meteorological sensors, water level sensors, soil moisture sensors and tilt sensors in different regions, as shown in Figure 7. A fifth site at Adygene Lake is currently being installed.

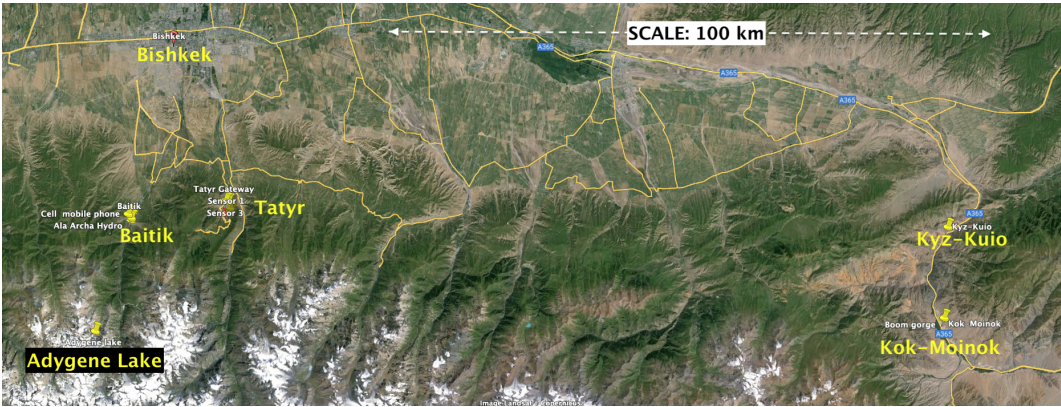


Figure 7. Location of the five pilot sites for the environmental sensors installations

7.1. Baitik and Ala Archa Hydropost

The selection of this site was strategic, not only due to its location but also due to the unique opportunity it presents for comparing data with existing meteorological stations. By analyzing and comparing data gathered from these stations, the team validated the consistency, accuracy, and relevancy of the data generated by the LoRaWAN-enabled technology. The Baitik Meteorological Center, located in a significant climatic area, offers critical insights into local and regional weather patterns. The Ala Archa Hydropost plays a crucial role in monitoring water levels, enabling early detection and warnings of potential floods. The installation of LoRaWAN-enabled sensors at these locations greatly enhances the timeliness of data collected, further aiding in the decision-making process for disaster management.

7.2. Tatyr

The Tatyr landslide is geographically situated 30-40 km south of Bishkek. Administratively, the area is part of the Arashan aiyl district within the Alamedin district. Formed on a north-facing slope, the landslide extends for 1510 meters, with a width varying between 250 to 300 meters, and a thickness ranging from 10 to 15 meters. The landslide involves loamy soils, encompassing the underlying Paleogene-Neogene age rocks. Its formation is primarily attributed to anomalous atmospheric precipitation, coupled with the impact of groundwater emerging as springs and a proximate tectonic fault. The last significant activity was recorded in 2004 when the landslide moved 70 meters following a year of intense rainfalls. The landslide lies along the route to popular skiing locations and tourist destinations. Previously, monitoring was performed manually through periodic on-site visits. The site's proximity to Bishkek city made it an ideal pilot location for this research project, allowing for swift sensor validation of research goals. Besides the meteorological sensors, five soil temperature and moisture sensors were sunk at different depths and distances from the gateway as shown in Figure 8.



Figure 8. Installation of soil temperature and moisture at the Tatyr landslide site

Being this a landslide prone area, 5 tilt sensors were also deployed to measure the terrain inclination, as an early warning for potential landslide events. So a total of 23 variables are collected from this site, since the deployed weather station has sensors for air temperature, air humidity, barometric pressure, solar irradiation and battery voltage.

7.3. Boom Gorge

The ISOC Kyrgyz Chapter team, in response to a request from the Ministry of Emergency Situations, installed two LoRaWAN-enabled Meteostations and additional sensors in the Boom Gorge. This initiative aims to enhance the understanding and monitoring of the region's distinct microclimate, providing key data to inform preemptive action and disaster management.

The Boom Gorge, as shown in Figure 9, is marked by unique orographic features and has a complex geological structure: this is the reason why it has historically grappled with the impacts of heavy rainfalls. These intense precipitations often trigger powerful mudflows, draining from side valleys onto railroads and roads, causing significant infrastructural damage and posing public safety risks. Given the challenges posed by climate change, obtaining accurate and reliable local environmental and meteorological data in this region is becoming increasingly crucial. Therefore, two sets of environmental sensors were deployed; one at Kok-Moinok and the other at Kyz-Kuio.



Figure 9. Installation at Boom Gorge.

7.4. Adygene Lake

The latest installation has been at Adygene Glacier Mountain Lake, strategically situated 60 km south-southwest of Bishkek. Nestled at an altitude of 3600 m in the upper reaches of the Adygene river valley, a left-side tributary of the Ala-Archa river, this high glacier lake serves as a focal point for the deployment of IoT sensors aimed at monitoring glacial lake outburst floods.

The Adygene lake complex, positioned on the side of the glacier, encompasses three additional lakes to the South and Southeast. The South easternmost lake, situated at an elevation of 3640 meters, was formed along the northern edge of the glacier, with its Southern coast adjoined to the glacier itself. Measuring 188 meters in length and 70 meters at its widest point, the lake has a perimeter of 550 meters, covering an area of 17142 square meters. A stream flows from the northeastern side, eventually merging with a small moraine lake after a 330-meter journey. Additionally, the southern part of the lake houses ten more small moraine lakes.

This installation has been very challenging due to the altitude and to the rough terrain as seen in Figure 10. The desk analysis of the data showed that there are some spots that could be used for establishing connection between LoRaWAN-enabled devices and the nearest cellular towers located at a distance of 25 and 40 km from the lake in Chuy valley.



Figure 10. Installation at Adygene lake.

Considering that the pilot location is located at high altitudes, where harsh winter conditions prevail, the construction of the masts and tower had to be carefully planned.

The construction team prepared all ready-to-build parts and materials, carried all materials on foot to the base and finished the construction of the tower for the meteorological sensors and the Gateway, as well as the installation of the photovoltaic system for powering.

Based on consultations with the experts from CAIAG, Institute of Water Problems under the Academy of Sciences of the Kyrgyz Republic as well as ICTP, a bigger panel had to be installed to guarantee powering for the gateway.

7.5. Powering

Given their limited energy consumption, all the sensors are battery powered. This is because the sensors wake up only every 10 minutes, to make a measurement and send the relevant data.

The weather station has additionally a small solar panel, that is used for measuring the solar irradiation as well as for charging the internal battery. The vendor states that the station can operate for up to 3 months in the absence of sunlight.

On the other hand, the UG67 Gateway must be always on, to be able to receive any message from the sensors. It has a peak consumption of 4.8 W, so the maximum consumption per day is $4.8 \times 24 = 115.2$ Wh. Our own measurement show that the average power consumption is around 3.6 W.

The amount of solar irradiance in Kyrgyzstan varies significantly with the elevation of the place. Looking at the historical data available² it is found that in the last 28 years the minimum irradiance on the worst month was 1.4 kW/m², that is 1.4 peak sun hours (PSH). Since solar panels are locally manufactured in Kyrgyzstan and quite inexpensive, we decided to deploy 305 watt peak solar panels made by NewTek, with up to 40 volts, 9.87 A output. In the worst month, this panel provides $1.4 \times 305 = 427$ Wh per day, more than enough to supply the load and charge the battery even after many no sun days. The 12 V battery chosen has a capacity of 100 Ah, so it can feed the UG67 for up $1200 / 115.2 = 10.4$ days. A WP30D charge controller is installed at the output of the solar panel to charge the battery and supply a constant voltage to the load.

8. Training

ICTP's experience in many international projects has demonstrated that training and capacity building are fundamental ingredients for the success and sustainability of any technological endeavor. Consequently, we have organized several on-line training activities since the beginning of the project, addressing topics like environmental sensors, wireless propagation, RF for IoT, Low Power Wide Area Networks (LPWAN), LoRaWAN technology, Sensors and Gateways installation criteria, MQTT and Data Visualization, and Photovoltaic Power Systems. A forum on "Application of innovative technologies in monitoring and forecasting of climate change and natural disasters" was held in Bishkek in December 2023 with some lecturers participating remotely. Simultaneous translation for Russian, English, Kyrgyz was provided to facilitate a wider engagement.

Additionally, face-to-face lectures in Bishkek as well as hands-on on-site training was delivered during the equipment deployment. On April 2023 a Workshop on LoRaWAN with devices demonstrations was attended by representatives from CAIAG, Ministry of Emergency Services, and Kyrgyz universities.

9. Preliminary Results

The sensors have been running for over an year and we can start gathering some insights from their behavior.

9.1. Temperature Sensor: Comparison with Calibrated Weather Station

In Baitik we installed our solution next to a calibrated weather station, as we wanted to compare the temperature values over time. Figure 11 shows the results of the comparison in a six month time span, from May to December 2023. The first dataset received from the Kyrgyz Agency of Hydrometeorology are temperatures from the reference weather station (solid yellow line) while the second dataset is showing the IoT weather station (dashed orange line). Both datasets are plotted against the same time reference. The two datasets show a high degree of correlation, with the second dataset generally following the pattern of the first dataset but with some small deviations. Note that in the second dataset there are two gaps, one between August and September 2023, and the other from December 2023 to January 2024. This was due to the database being offline for problems that have later been solved.

² https://re.jrc.ec.europa.eu/pvg_download/map_pdfs/G_opt_KG.png, and <https://power.larc.nasa.gov/beta/data-access-viewer/>

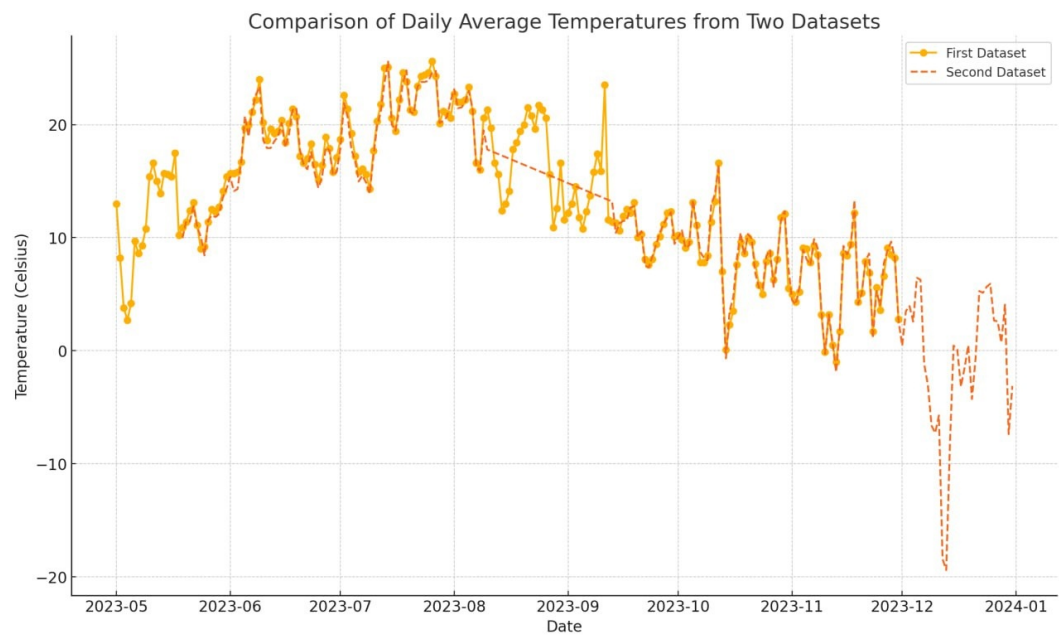


Figure 11. Comparison of temperature measurements over time from two instruments: reference weather station (solid yellow line) and the IoT weather station (dashed orange line).

9.2. Water Level Sensor

Figure 12 shows the water level sensor measurements from June 2023 to February 2024. These values were obtained by an ultrasonic distance meter installed below a bridge and fitted with a LoRaWAN transmitter, at about 200 m from the Baitik Gateway. The water level starts around 0.45 meters in June 2023, peaks at over 0.8 meters around August 2023, and then gradually decreases to around 0.4 meters by February 2024. The trend shows a notable increase during the middle of 2023, followed by a steady decline towards the end of 2023 and early 2024, following the expected water level trend linked to snow melting in the spring. Again there is a gap in the data between August and September 2023 due to the above mentioned issues.

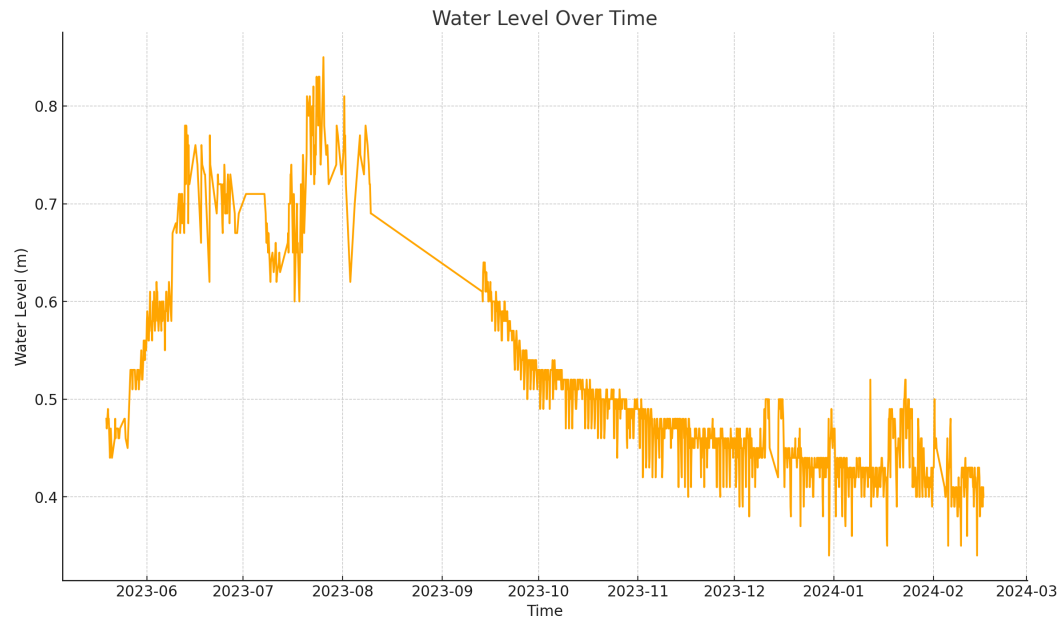


Figure 12. Water level sensor measurements.

9.3. Precipitation Levels

The results of the daily precipitation rate gathered at Kiz-Kuio (blue trace) and Kok-Moinok (orange trace) for the period between April 22 and May 22 are shown in Figure 13.

Despite the two sites being only 12 km apart, one can notice that there are some coincidences but also significant variations. This highlights the importance of having many meteorological sensors to obtain a more accurate weather model.

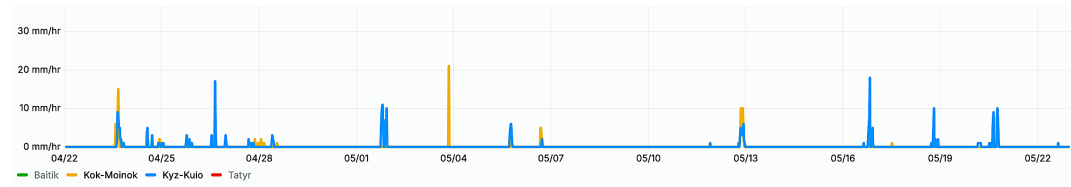


Figure 13. Daily precipitation values recorded at Kiz-Kuio and Kok-Moinok during one month using the IoT rain gauge.

9.4. Solar Irradiation

Figure 14 shows the distribution of values of solar irradiation measurements. As can be observed, most measurements are in the 900 W per square meter range. Nevertheless, given the mountainous terrain involved, there are many points at much lower value. This is why we chose to standardize to a 305 Wp (peak) solar panel for all the sites, except Adygene lake that being at such a high elevation is prone to have some period of very low irradiation.

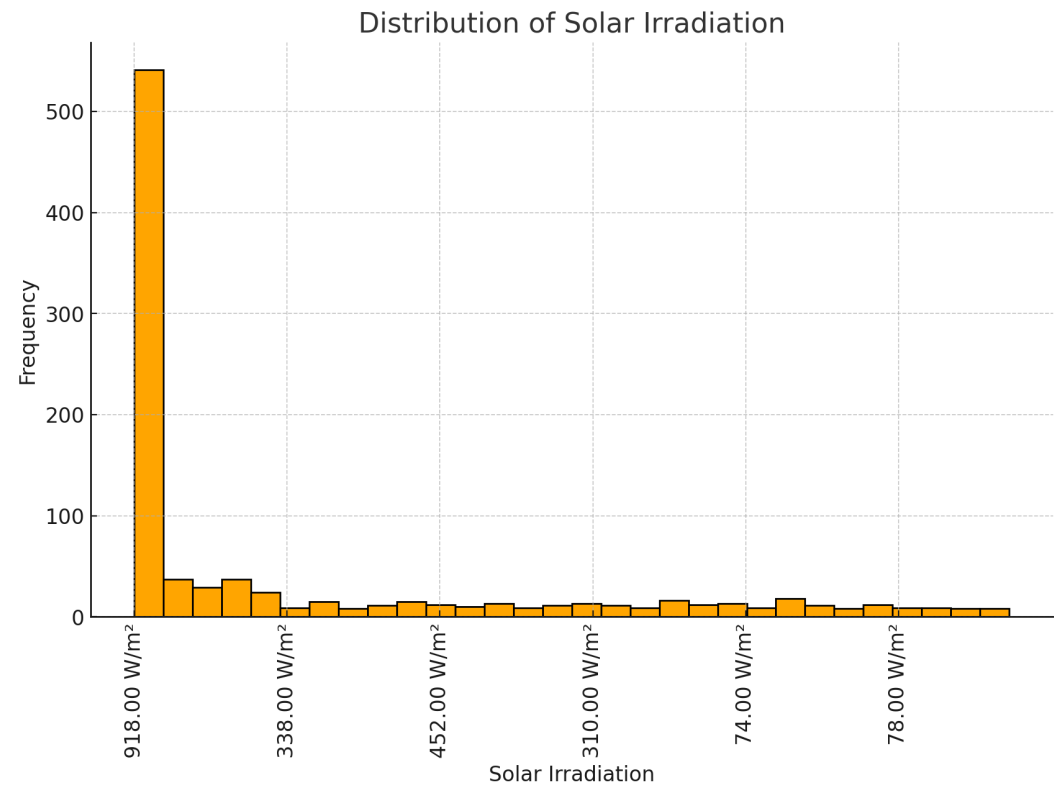


Figure 14. Distribution of solar irradiation measurements.

Referring to Figure 6, one can see that in a Summer day the peak levels of solar irradiance are similar for different sites, but there can be wide fluctuations due to clouds.

9.5. Received Signal Level

To assess the probability of landslides, several soil temperature and moisture sensors were installed in the Tatyrt site. Figure 15 shows the variation of the received signal level over a week time. Device 2 (green trace) was buried at a depth of 100 cm, 330 m away from the gateway. Device 3 (yellow trace) was buried at a depth of 20 cm, 260 m away from the gateway. Device 5 (blue trace) was buried at a depth of 20 cm, 1500 m away from the gateway. Notice that the strongest signal was received from Device 2, despite being buried at the deepest level. On the other hand, Device 5, which was at the longest distance, showed greater variability of the signal strength. Keep in mind that LoRa signals can be reliably decoded at signal levels as low as -137 dBm. Therefore much longer distances can be reached from the same gateway.

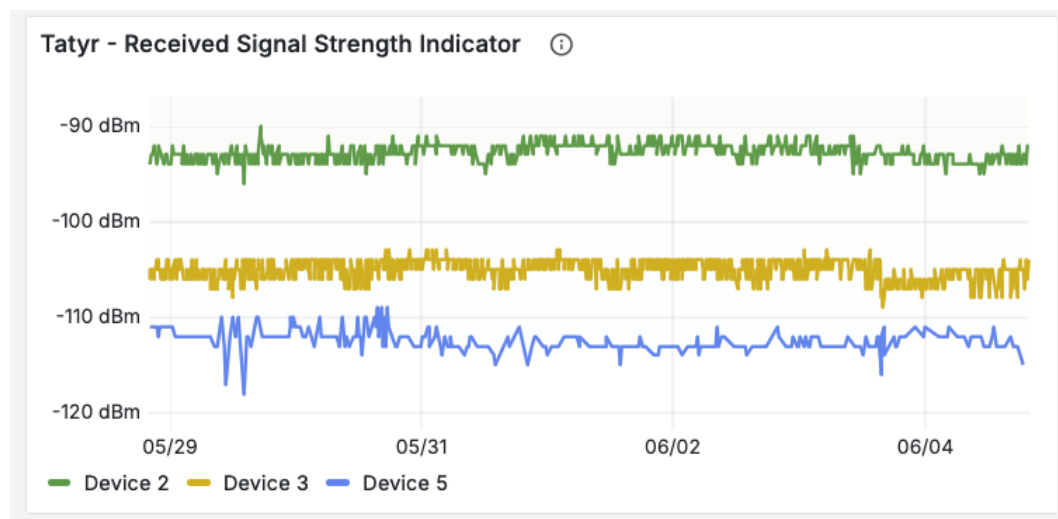


Figure 15. Distribution of solar irradiation measurements.

10. Conclusions

We have presented the planning and deployment of a wide arrange of wireless environmental sensors in the challenging scenario of a mountainous country. The limited Cellular coverage was addressed by deploying LoRaWAN gateways, which proved well suited to satisfy the requirements of the current application, while their agnostic nature can be leveraged to provide additional services, like messaging in places devoid of cellular coverage or for people who cannot afford the associated recurring costs. The meteorological sensors installed are less expensive than traditional automatic weather stations (AWS) without significant compromises in accuracy. The deployment of river water level, soil humidity and tilt sensors also helps in mitigating environmental disasters effects. Data is stored inside the country, thus preserving privacy, but made available to international stakeholders with legitimate interest. Several international organizations have shown interest in deploying additional sensors of this type.

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