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LORAWAN WIRELESS COMMUNICATION NETWORK FOR NEAR REAL-TIME WATER CONSUMPTION DATA COLLECTION: ARCHITECTURE AND DIMENSIONING FOR THE PIGEON DISTRICT, NGALIEMA, KINSHASA

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ABSTRACT

Rapid urbanization and the growing pressure on water resources make accurate consumption measurement a prerequisite for effective distribution management. In rapidly expanding areas of Kinshasa such as Pigeon, two challenges coexist: meters are either absent or non-functional for many connections, and meter reading still relies on manual visits, leading to estimated or flat-rate billing. This study proposes and dimensions a LoRaWAN wireless network architecture for near real-time water consumption data collection in the Pigeon district (Ngaliema, Kinshasa). The methodology is based on a five-layer reference architecture (perception, radio access, backhaul, platform, and application) with cross-cutting security, and an analytical dimensioning model. A pilot cluster of 50 smart meters is analyzed through link budget, time-on-air, duty cycle, and collision probability calculations. The results show that a pilot of 50 meters in a 0.5 km^2 area is served by a single gateway with a packet delivery ratio (PDR) ranging from 90% to 99%. Extrapolation to the entire district (~7,000 connections) reveals that capacity, rather than coverage, dictates the number of gateways required: at least 3 to 8 gateways are needed for 50-byte messages every 15 minutes, and 1 to 2 for hourly reporting. The integration of technical and educational monitoring, along with the proposed scalable and cost-effective framework, provides a practical tool for deploying smart water metering infrastructures in densely populated urban environments, contributing to sustainable urban water management.

Keywords: Lorawan; Smart Water Metering; LPWAN; Automated Meter Reading; Network Dimensioning; Kinshasa.

1 INTRODUCTION

1.1 Context and Challenges of Urban Water Management

Access to reliable and quality water is a robust indicator of a region's development level. In the Democratic Republic of the Congo (DRC), rapid urbanization, parcel fragmentation, and the scarcity of water resources pose major challenges for municipalities in Kinshasa. In high-growth neighborhoods such as Pigeon, the efficient management of water distribution has become a critical priority [1].

Two main issues are currently recorded. First, traditional metering systems, often based on first-generation Automated Meter Reading (AMR) infrastructure, present significant limitations: lack of real-time monitoring, tedious manual readings, reading errors, and approximate billing [2]. Second, a large number of connections either lack meters entirely or possess old, worn-out, and unusable equipment. This situation leads to flat-rate billing based on estimations (e.g., house size or number of containers used) rather than actual consumption.

The emergence of Internet of Things (IoT) technologies and Low-Power Wide-Area Networks (LPWAN) offers new perspectives for modernizing water metering infrastructures. Among these, LoRaWAN is particularly attractive for operators as it operates in license-free bands and allows for the deployment of a private network [3, 4]. However, the capacity of LoRaWAN is limited by its ALOHA-type medium access and regional duty cycle rules [5, 6]. The claim that "one gateway can serve thousands of meters" therefore heavily depends on the reporting interval, message size, and spreading factor distribution, and must be verified for each deployment. This question has not yet been addressed for the Pigeon district.

1.2 Problem Statement and Objectives

The central problem of this study lies in designing a wireless communication network architecture adapted to the specific constraints of the Pigeon district: high urban density, building diversity, low energy consumption requirements, and reliability. The main objective is to propose a wireless network architecture for the near real-time collection of water consumption data, allowing the water distribution company (REGIDESO) to better manage the monthly billing process.

The contributions of this article are: (i) a five-layer reference architecture with its hardware and software components; (ii) an analytical dimensioning of a pilot cluster of 50 meters (link budget, time-on-air, duty cycle, collision probability); (iii) an extrapolation to the ∼7,000 connections of the district showing that capacity, not coverage, determines the number of gateways; and (iv) design recommendations and a list of data to be collected during a field pilot.

2 MATERIALS AND METHODS

2.1 Study Area

The Pigeon district is located in the Ngaliema municipality of Kinshasa, at approximate coordinates of 4°23' S and 15°16' E. It has approximately 7,000 dwellings, and its water pipes reach almost all plots. The terrain is hilly, with ravines on the periphery, and the housing is dense and heterogeneous.

The current constraints of meter reading are severe: the quasi-totality of plots no longer has a functional meter. The company sensitizes subscribers but lacks a rigorous control policy, leading to flat-rate billing. The subdivision of plots increases the number of consumers and forces agents to travel more points on foot. When no reading exists, billing relies on estimations, making payment regularity the only means of keeping access to water.

2.2 System Requirements

The requirements derived from these constraints are summarized in Table 1.

Table 1: System requirements.

ID	Requirement	Target
E1	Radio coverage in dense urban environment	All ~7,000 connections, including meters in underground boxes
E2	Reporting interval (periodic, near real-time)	15 min by default; configurable from 15 min to 24 h
E3	Application payload per message	50 bytes
E4	Battery-powered meter autonomy	≥ 10 years (manufacturer: up to 15 years)
E5	Security	OTAA activation, AES-128 at network and application layers
E6	Bidirectional communication	Downlink for configuration and alarms
E7	Scalability	From a 50-meter pilot to ~7,000 meters
E8	Metrological compliance	MID / ISO 4064 (head loss ≤ 0.63 bar at Q3)

2.3 Technology Selection

A comparative study of wireless technologies (Table 2) was conducted. LoRaWAN was selected due to its long-range capabilities (2–15 km in urban areas), low power consumption, cost-effectiveness (license-free ISM bands), and robust security (AES-128).

Table 2: Wireless technologies and their characteristics.

Criterion	Wi-Fi	BLE	ZigBee	LoRaWAN	NB-IoT	LTE-M	Sigfox
Standard	IEEE 802.11	Bluetooth 5.x	IEEE 802.15.4	LoRa Alliance	3GPP Rel. 13	3GPP Rel. 13	Sigfox
Network Type	WLAN	WPAN	WSN / WPAN	LPWAN	Cellular LPWAN	Cellular LPWAN	LPWAN
Range	20–100 m	10–100 m	10–300 m	2–15 km (urban)	Several km	Several km	10–50 km
Data Rate	54 Mb/s to >1 Gb/s	125 kb/s–2 Mb/s	20–250 kb/s	0.3–50 kb/s	Up to 250 kb/s	Up to 1 Mb/s	100 b/s
Consumption	Very High	Very Low	Low	Very Low	Low	Medium	Very Low
Topology	Star	Star	Mesh	Star-of-Stars	Cellular	Cellular	Star
Battery Life	Few days	Several years	2–5 years	5–10 years	5–10 years	3–5 years	10 years
Security	WPA2/WPA3	AES-128	AES-128	AES-128 (Network + App)	LTE (SIM)	LTE (SIM)	AES-128

2.4 Proposed Architecture

The proposed network is a hierarchical wireless architecture organized into five layers and a cross-cutting security layer (Figure 1).

- **Perception Layer:** Smart water meters measure consumption, are identified by a unique ID, and transmit data via LoRa.
- **Radio Access Layer:** LoRaWAN gateways in a star-of-stars topology relay each frame to the network server.
- **Backhaul Layer:** Routes frames over an IP link (Ethernet or 4G) secured by TLS.
- **Platform Layer:** Includes the LoRaWAN network server, MQTT broker, processing services, and database.
- **Application Layer:** Provides dashboards, billing, alerts, and mobile access for administrators, network managers, and subscribers.

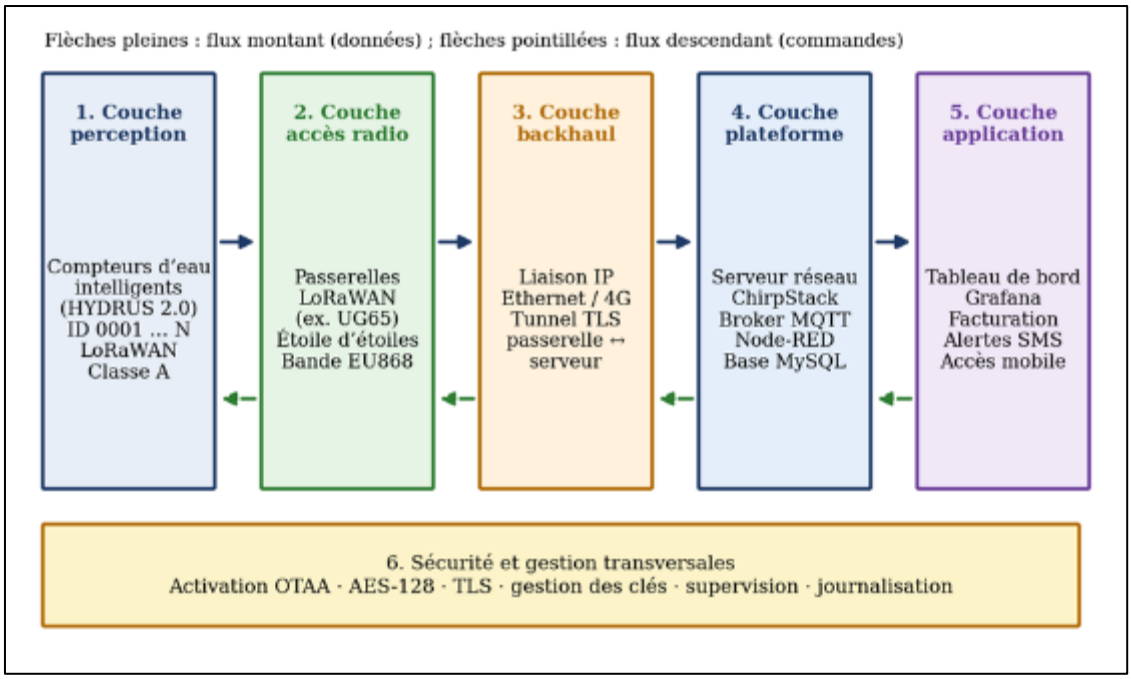


Figure 1: Proposed five-layer architecture with cross-cutting security

The hardware and software components selected are detailed in Table 3. The Semtech SX1262 is the LoRa transceiver integrated into the meter's radio module. The sensitivity of –148 dBm indicated in its datasheet corresponds to the narrowest band (7.8 kHz); for the 125 kHz band used by LoRaWAN, the sensitivity at SF12 is approximately –137 dBm, a value retained in the link budget below.

Table 3: Selected hardware and software components.

Component	Model	Main Characteristics	Role
Smart Meter	Diehl HYDRUS 2.0 LoRaWAN	Ultrasonic; LoRaWAN Class A; 868/915 MHz; battery up to 15 years; IP68; accuracy ±2%; configurable reporting from 15 min to 24 h; AES-128	Measures consumption and transmits via LoRaWAN
LoRa Radio	Semtech SX1262	150-960 MHz; up to +22 dBm; SF5-SF12; bandwidth 7.8-500 kHz; standby current < 1 µA	LoRa link between meter and gateway
Gateway	Milesight UG65	8 channels; 868/915 MHz; sensitivity -140 dBm; Ethernet, Wi-Fi, 4G; PoE; > 2,000 nodes	Collects frames and transmits to network server
Network Server	ChirpStack	Open source; LoRaWAN 1.0/1.1; multi-gateway; REST/gRPC API; MQTT integration	Manages network, devices, and communications
MQTT Broker	Eclipse Mosquitto	Open source; MQTT v5; QoS 0, 1, 2; TLS; WebSocket	Exchanges data between network server and applications
Database	MySQL	Relational, open source; compatible with Grafana and Node-RED	Stores consumption and system data
Supervision	Node-RED + Grafana	Real-time dashboards; alerts; API; data export	Displays data, statistics, and alerts

The application protocol is MQTT (Message Queuing Telemetry Transport), a publish/subscribe protocol operating over TCP. A central broker collects publications and subscriptions and transmits messages between clients. The data path is: meter → LoRa → gateway → ChirpStack → MQTT broker → Node-RED → MySQL → Grafana.

2.5 Dimensioning Model

The dimensioning involves four steps. The assumptions are listed in Table 4.

Table 4: Dimensioning assumptions.

Parameter	Value	Comment
Band / Regional Parameters	EU868 (863-870 MHz), 1% duty cycle	To be confirmed with the national regulator (ARPTC)
Bandwidth, Coding Rate	125 kHz, CR 4/5	Standard LoRaWAN uplink settings
Application Payload	50 bytes	Requirement E3
MAC/PHY Overhead	13 bytes	MHDR, DevAddr, FCtrl, FCnt, FPort, MIC
Reporting Interval (T_{rep})	15 min (96 messages/day)	Also tested: 30 and 60 min
Transmit Power / Antenna Gains	14 dBm; 0 dBi (meter); 3 dBi (gateway)	Typical EU868 values
Receiver Sensitivity (SF12)	-137 dBm	SX1262, 125 kHz
Fading Margin	10 dB	Assumption
Path Loss Exponent (n)	3.0; 3.5; 4.0	Dense urban range (Rappaport, 2002)
Additional Loss (box/indoor)	0, 10, 20 dB	Meters are often in boxes or buried
Channels per Gateway	3 (default) or 8	The UG65 handles 8 channels

Step 1: Coverage. Propagation is described by the log-distance model:

$$PL(d) = PL(d_0) + 10 \cdot n \cdot \log_{10}(d/d_0) + X_\sigma \quad (1)$$

where $d_0 = 1$m and $PL(d_0) = 20 \cdot \log_{10}(4\pi d_0/\lambda) = 31.2$dB at 868 MHz. The maximum allowable path loss is:

$$PL_{max} = P_{tx} + G_{tx} + G_{rx} - S_{rx} - M_f - L_{sup} \quad (2)$$

and the maximum range is obtained by inverting equation (1). A hexagonal cell of radius R has an area $A = \left(3\sqrt{3}/2\right)R^2$, and the number of gateways required to cover a district of area S is:

$$N_{cov} = \left\lceil S/\left(\left(3\sqrt{3}/2\right) \cdot R^2\right)\right\rceil \quad (3)$$

Step 2: Time-on-Air and Duty Cycle. According to the Semtech modem guide, the symbol duration is $T_{sym} = 2^{SF}/BW$, the preamble lasts $\left(n_{pre} + 4.25\right) \cdot T_{sym}$with $n_{pre} = 8$, and the number of payload symbols is:

$$n_{pl} = 8 + \max\left\{\left\lceil(8 \cdot PL - 4 \cdot SF + 28 + 16 \cdot CRC - 20 \cdot H)/\left(4 \cdot (SF - 2 \cdot DE)\right)\right\rceil \cdot (CR + 4)0\right\} \quad (4)$$

where PL is the PHY payload in bytes (50 + 13 = 63), CRC = 1, H = 0 (explicit header), CR = 1 (coding rate 4/5), and DE = 1 for SF ≥ 11 at 125 kHz. The time-on-air is $ToA = \left(n_{pre} + 4.25 + n_{pl}\right) \cdot T_{sym}$, and the duty cycle of a meter is $\delta = ToA/T_{rep}$, which must remain below 1%.

Step 3: Traffic and Collisions. With N meters, $N_g$gateways, N_{ch}channels, and $\lambda = 1/T_{rep}$, the normalized load offered per channel and per gateway and the packet delivery ratio (PDR) in a pure ALOHA model are:

$$G = \left(N/N_g\right) \cdot \lambda \cdot ToA/N_{ch},\ PDR = e^{-2G} \quad (5)$$

Step 4: Data Volume. The daily volume is $V = N \cdot B \cdot \left(86{,}400/T_{rep}\right)$, where B is the application payload in bytes.

3 RESULTS

3.1 Pilot Cluster: Traffic and Time-on-Air

The pilot cluster comprises 50 meters over 0.5 km², corresponding to 50 connected plots, i.e., a density of 100 meters/km². With a 15-minute reporting interval, each meter sends 96 messages per day, i.e., 96 × 50 = 4,800bytes (4.69 KiB) per day per meter. The pilot thus generates 50 × 4,800 = 240,000bytes, or 234 KiB per day. The average application throughput is 400 bits/900 s = 0.44 bit/s per meter and 22 bit/s for 50 meters, which is negligible compared to the capacity of a gateway.

Table 5: Time-on-Air and Duty Cycle of a 63-byte frame (125 kHz, CR 4/5), 96 messages/day.

SF	Bitrate (kb/s)	Time-on-Air (s)	Duty Cycle (%)
7	5.47	0.118	0.013
9	1.76	0.390	0.043
10	0.98	0.698	0.078
12	0.29	2.793	0.310

At SF12, a message lasts 2.79 s, and a meter transmitting 96 times a day occupies the channel 0.31% of the time, below the 1% limit.

3.2 Link Budget and Coverage Radius

With the assumptions in Table 4, $PL(d_0) = 31.2$dB and $PL_{max} = 14 + 0 + 3 - (-137) - 10 = 144$dB in the absence of additional loss. Table 6 gives the corresponding maximum range at SF12.

Table 6: Maximum range at SF12 (km).

Additional Loss	PL_{max}(dB)	n = 3.0	n = 3.5	n = 4.0
0 dB	144	5.75	1.67	0.66
10 dB	134	2.67	0.86	0.37
20 dB	124	1.24	0.45	0.21

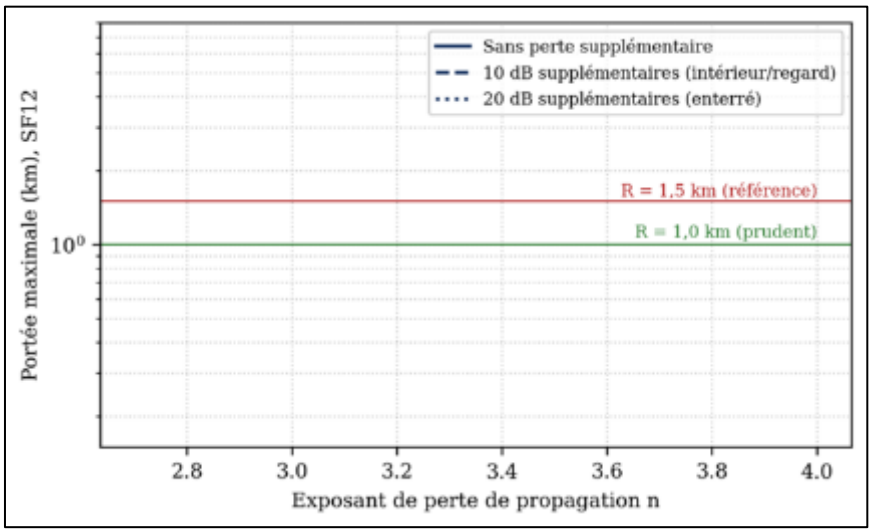


Figure 2: Maximum range at SF12 as a function of the path loss exponent

The 1.5 km radius used in the preliminary design is therefore only achieved for n ≈ 3.5 without additional penetration loss. With 10 dB additional loss, the range drops to about 0.9 km. A conservative radius of 1.0 km is therefore adopted in addition to the 1.5 km reference. A 0.5 km^2 disk has an equivalent radius of 0.40 km: the pilot area is thus covered.

3.3 Pilot Cluster: Collision Probability

For 50 meters served by one gateway, the PDR is 99.6% at SF7, 98.6% at SF9, and 90.2% at SF12 with 3 channels; with 8 channels, it is respectively 99.8%, 99.5%, and 96.2%. The 90% design objective is therefore achieved in the pilot, even in the worst case where all meters use SF12.

3.4 Extrapolation to the Entire District

For the ~7,000 connections, the daily volume is 7,000 × 4,800o = 33.6 MB (32.0 MiB), the aggregated application throughput is about 3.1 kbit/s, and the backhaul load is negligible. The constraint lies on the radio channel. Table 7 gives the number of gateways required for coverage and Table 8 the number required for a PDR of at least 90% (8 channels).

Table 7: Gateways required for coverage, N_{cov} (hexagonal cells).

District Area S	R = 1.5 km	R = 1.0 km
2 km²	1	1
4 km²	1	2
6 km²	2	3

Table 8: Gateways required for capacity, N_{cap} (7,000 meters, PDR ≥ 90%, 8 channels, pure ALOHA).

Reporting Interval	Load 50 o, SF7	Load 50 o, SF9	Load 20 o, SF7	Load 20 o, SF9
15 min	3	8	2	5
30 min	2	4	1	3
60 min	1	2	1	2

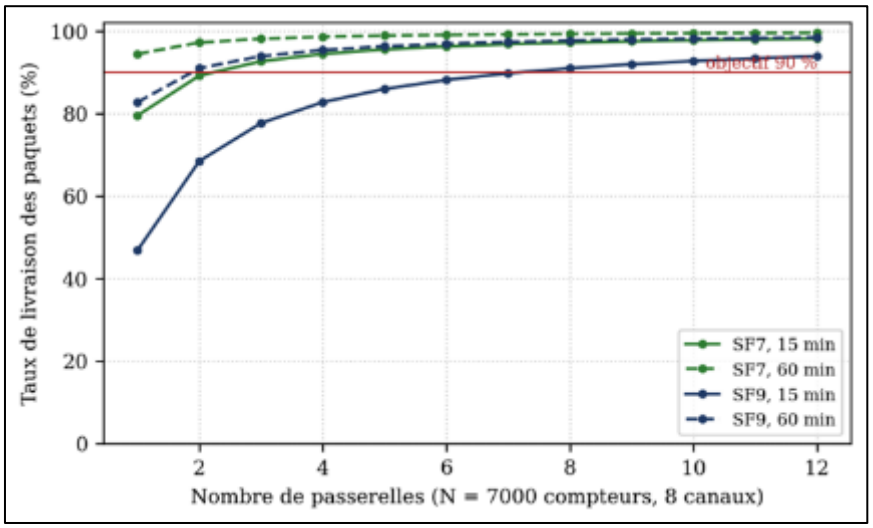


Figure 3: Packet delivery ratio as a function of the number of gateways for 7,000 meters

4 DISCUSSION

4.1 Comparison with Existing Solutions

Compared to traditional AMR systems, the proposed AMI architecture offers:

- **Near real-time monitoring:** Consumption is reported every 15 minutes, allowing continuous night flow to reveal leaks.
- **Automated and precise billing:** Bidirectional data transmission enables accurate and transparent billing, reducing estimation errors and disputes.
- **Reduced operational costs:** Remote reading, battery status diagnostics, and remote configuration reduce field interventions.

4.2 User Organization and Traceability

The proposed system ensures continuity in information management, from the meter to the billing application. This centralization helps reduce information loss, improve communication among stakeholders, and guarantee better traceability of the actions performed. The combination of technical management and educational monitoring (assigning tasks to learners, assessing responses, managing appeals) is a distinctive feature compared to standard commercial solutions.

Limitations

- **Analytical study:** No field measurements (RSSI, SNR, PDR) have yet been performed; propagation parameters (n, additional loss, fading margin) and spreading factor distribution are assumptions to be calibrated during the pilot.
- **Collision model:** The pure ALOHA model ignores capture and multi-gateway reception; a network simulation (e.g., NS-3 or LoRaSim) is necessary to refine N_{cap}.
- **Regulation:** The EU868 band and 1% duty cycle are assumed; the band and power authorized in the DRC must be confirmed with the regulator (ARPTC).
- **Backhaul dependency:** The gateway–server link relies on Ethernet or cellular coverage (4G/5G), which may present shadow zones.
- **Data security and privacy:** Consumption data reveals household habits and requires robust encryption, key management, and access control.
- **Investment cost:** Replacing or installing meters represents a significant cost for the company and subscribers; a cost-benefit analysis remains to be carried out.

4.3 Implications for Urban Water Management

A smart metering infrastructure would allow the company to optimize distribution according to actual demand, reduce water losses due to leaks and illegal connections, involve subscribers in more responsible consumption through mobile applications, and anticipate future capacity needs.

5 CONCLUSION

This study proposed a five-layer LoRaWAN architecture for the near real-time collection of water consumption data in the Pigeon district and dimensioned it analytically. A pilot of 50 meters over 0.5 km^2 is served by one gateway with a delivery rate of 90 to 99%, but a second gateway is recommended for redundancy. Extension to the ∼7,000 connections of the district is limited by capacity rather than coverage: at least 3 to 8 gateways are needed with 50-byte messages every 15 minutes, and 1 to 2 with hourly reporting. LoRaWAN therefore remains a suitable technology, provided that the reporting policy and gateway density are designed jointly.

Future work includes: (i) a field pilot to measure link quality and calibrate the propagation model, thereby validating the analytical results; (ii) a network-level simulation including capture and ADR; (iii) a cost-benefit analysis of deployment and operation; (iv) machine learning algorithms for predictive leak detection and demand forecasting; (v) mechanisms ensuring the integrity of consumption data for transparent billing; and (vi) the fusion of consumption data with environmental data for integrated water resource management.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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Disclosure of conflict of interest

The authors declare no conflict of interest regarding this manuscript.

Statement of ethical approval

The authors confirm that all procedures performed in this study involving human participants were in accordance with the ethical standards of the institutional and/or national research committee.

Statement of informed consent

Informed consent was obtained from all individual participants included in the study.

Data Availability

The calculation scripts and parameters used for Tables 5 to 8 can be provided upon request.

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