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Development of an Automatic Portable Calibrator for Tipping Bucket Rain Gauge (TBRG) Using a Load Cell and Simple Water Sensor

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Abstract: The tipping bucket rain gauge is an automatic rain gauge that can measure rain intensity in mm/hour. Accurate measurement of rain intensity requires calibration of the rain gauge to ensure traceability. Calibration of a tipping bucket rain gauge is related to the volume of water as a calibration medium and time so as to produce a discharge that can be converted into rain intensity. Technological developments can make tipping bucket rain gauge calibration automatic by utilizing an Arduino Mega2560 microcontroller, a load cell and a simple water sensor based on the LM393 comparator IC, and combined with a compact design printed using a three-dimensional printer so that it can be used for ex-situ calibration. The data produced by this tool can be downloaded via the application that was built and produces a file in Excel form.

Keywords: Arduino Mega2560; calibrator; load cell; and tipping bucket rain gauge

Introduction

Rain is a natural phenomenon that greatly influences life on Earth (Muflih et al., 2019). Rain is one part of the hydrological cycle which is the main source of water for living things. Rainfall provides water for domestic, agricultural and industrial purposes, as well as aquatic and non-aquatic ecosystems, and its measurement is considered the most important task in hydrology (Cantonati et al., 2020; Choi et al., 2023; Hamid et al., 2020). Extreme weather with high rainfall intensity that often occurs in Indonesia makes Indonesia a threat to hydrometeorological disasters, such as floods, droughts, storms and landslides (Basuki et al., 2022; Putri, 2021). The influence of the rain phenomenon on the lives of living creatures is so great that rain measurements are very necessary to support research and predictions regarding climate and weather change.

Automatic rain gauges have been installed throughout Indonesia by the Meteorology, Climatology and Geophysics Agency (BMKG) (Hakim & Dewi, 2021; Ramadhan et al., 2022; Mardyansyah et al., 2022). This type of automatic rain gauge is a tipping bucket rain gauge that is integrated with a server and database. The tipping bucket rain gauge can stand alone in the form of an Automatic Rain Gauge (ARG) or be part of a set of integrated measurement systems with other sensors such as the Automatic Weather Station (AWS) or Agroclimate Automatic Weather Station (AAWS). The number of uses of BMKG's tipping bucket rain gauges was 688 on ARG, 365 on AWS, and 103 on AAWS. Tipping bucket rain gauges have become popular due to their simple, durable, and inexpensive design; and most importantly, the ability to adapt to remote areas (Shedekar et al., 2016).

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Every measuring instrument, both digital and non-digital, has the potential to produce inaccurate data due to measurement errors. This causes the need to calibrate the measuring instrument to determine the correction value and measurement uncertainty of the instrument. Calibration aims to ensure instrument performance in accordance with the International System of Units (SI) or standards accepted by the community and in accordance with each specific requirement (Quartly et al., 2021). Head Regulation Masinde & Bagula (2015), states that weather observation equipment must be calibrated when it is first used and calibrated periodically when the equipment is installed in the field. According to the World Meteorological Organization, errors in TB rainfall gauges are caused by measurements, and can be systematic, random, and spurious (Muñoz et al., 2016). Based on this, the tipping bucket rain gauge that has been installed in the field also needs to be calibrated periodically.

The calibration process requires media, standard measuring instruments, and calibration methods. The media in the tipping bucket rain gauge calibration serves to produce a simulation of rain flow. The water flow must be regulated in such a way as to produce a constant water discharge. Several studies regarding the calibration of tipping bucket rain gauges mention the components used to regulate the water discharge in the calibration medium, namely the use of a clamp (Sypka, 2019) and a peristaltic pump (Santana et al., 2018). Apart from the need for media for calibration, choosing the right calibration method is also needed to determine the error value in the tipping bucket rain gauge. The method for calibrating a tipping bucket rain gauge in general is to compare the water discharge value of the calibrator (ml/s) with the measurement results of the tipping bucket rain gauge in the form of rain intensity (mm/hour).

Currently, there are automatic calibration media for tipping bucket rain gauges that have been mass produced by manufacturers. Officers can control the calibrator's work process and print calibration results certificates via an application on the computer. However, this system can only be used in laboratories. Meanwhile, the tipping bucket rain measuring calibrator used for field calibration is the Field Calibration Device (FCD). FCD functions as a tube water reservoir which is used to hold and drain a certain amount of water with a certain discharge. However, the tipping bucket rain gauge calibration process using FCD is still manual and relies on the skills of the calibration officer. This can be a source of measurement error due to human error. The need for tipping bucket rain gauge calibration is the basis for the need to develop a tipping bucket rain gauge calibrator based on the strengths and weaknesses of currently existing calibrators (Segovia-Cardozo et al., 2021).

Research and development regarding automatic field calibrators for tipping bucket rain gauges has been carried out and resulted in a web-based tool and is named Web Based Rain Gauge Calibrator (WBRGC) Version (Wijonarko et al., 2019). This tool is an automatic tool similar to a calibrator in a laboratory. However, WBRGC Version 1 still needed development due to the presence of air bubbles in the water tube, so the tool was developed into WBRGC Version 2 (Wijonarko et al., 2020; Huang et al., 2021; Bello et al., 2023). In addition to eliminating this bias, the development from WBRGC Version 1 to Version 2 resulted in a larger calibrator design and physical dimensions.

Issues from previous research encouraged researchers to look for alternative components and designs for automatic field calibrators for tipping bucket rain gauges. Apart from the type of optoelectronic sensor used in WBRGC Version 2, there are other sensors that can be used to measure the volume of water in a container. Research conducted by (Wang et al., 2018) states that load cells can be used to measure water depth and can detect depth changes of 1 mm. Other research conducted by (Agustine et al., 2024) also shows that load cells can be applied to monitor the volume of infusion fluids and can be used as a parameter when the flow of infusion fluids is to be stopped when it reaches a certain level.

Apart from load cells, sensors that can be used to measure liquid volume are two electrodes that will conduct electric current connected to water. Research by (Abdullahi et al., 2019) shows the use of a capacitive electrode sensor made from a Printed Circuit Board (PCB) and a comparator module to measure water depth. Apart from that, (Samijayani et al., 2014) uses a simple sensor, namely two conductor plates and a series of comprator modules to detect water levels in flood detection. Based on the explanation of the problems and conjectures for solutions to the problems mentioned above, researchers are encouraged to conduct research on automatic field calibrators for tipping bucket rain gauges which are more practical and still comply with the calibration method recommended by WMO in the Guide to Instruments and Methods of Observation (Segovia-Cardozo et al., 2023).

Method

This research aims to develop and perfect existing research products. The steps taken include problem formulation, literature review, product design, product preparation, and product validation. This research is divided into three parts, namely the first is hardware, programs on hardware and programs for applications on laptops.

System Block Diagram

The control center of the calibrator unit is an Arduino Mega2560 microcontroller. Arduino is an open source computing platform in the form of a single board microcontroller. The microcontroller in Arduino can be reprogrammed. The steps taken to program Arduino are by using the Arduino language and Arduino IDE (Pratomo & Perdana, 2017). There are electronic components to control water flow, including two solenoid valves and one 12V DC pump. A solenoid valve is an electrically controlled electromechanical device used to regulate the flow of liquids or gases (Angadi & Jackson, 2022).

The water reservoir body is made of cylindrical acrylic material and other parts such as the tube lid and holder are printed with a three-dimensional printer. Meanwhile, the sensor used to regulate the volume of water entering the water tube is a 5 kg load cell and a simple water sensor based on the IC LM393. A load cell is a transducer that measures force and produces an output in the form of an electrical signal. The load cell has four strain gauges in a Wheatstone bridge configuration to detect resistance measurements.

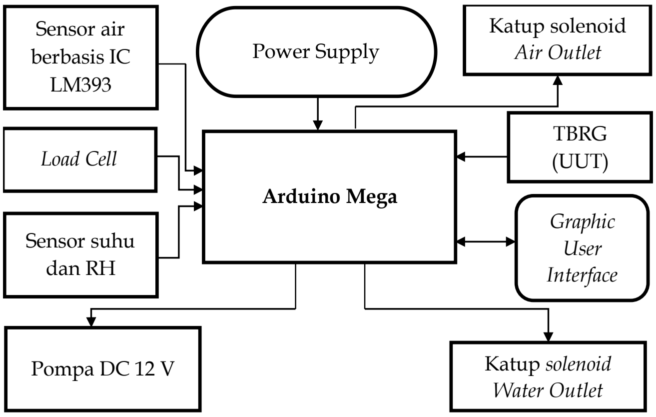


Figure 1. Block diagram of the system

A simple water sensor is two conductor plates connected to the LM393 comparator IC. The output of the load cell and simple water sensor is a command indicator for the water filling system to stop or continue, as well as an indicator that the water is ready to flow or stop flowing into the tipping bucket rain gauge. Apart from that, there are supporting components, namely the temperature sensor and RH DHT11 which function to measure environmental conditions during calibration. The power supply is a 12V DC battery connected to a microcontroller as a source of electric current in the system. User Interface (UI) as a media interface with users to run the tipping bucket rain measuring calibrator system and calibration data processing. The Unit Under Test (UUT) or tool being calibrated, namely a tipping bucket rain gauge, is connected to a microcontroller so that the microcontroller can calculate the tip that occurs during the calibration process.

Program Flow Diagram on Arduino

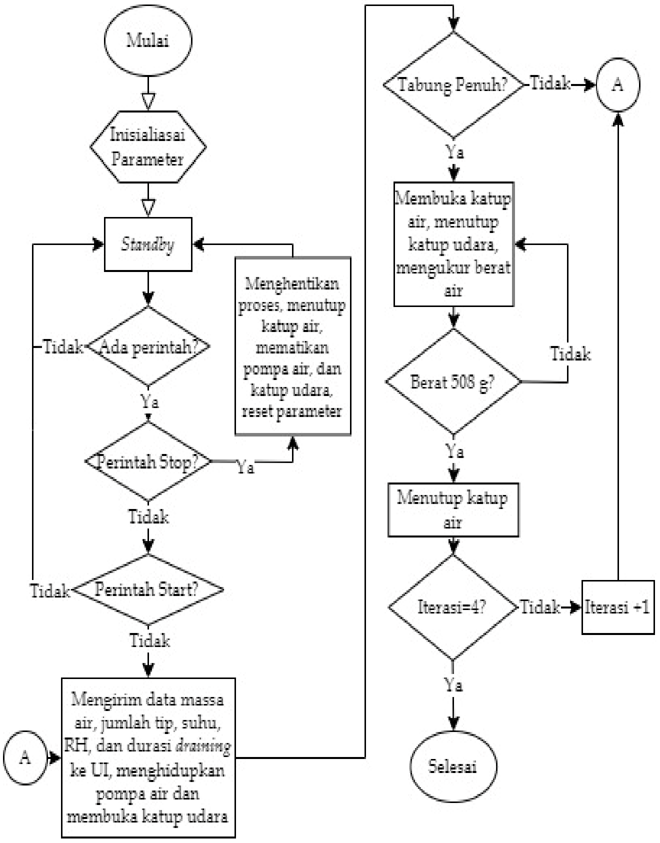


Figure 2. Flow Diagram on Arduino

Program Flow Diagram in Applications

In (Dunkerley, 2024), the information that needs to be reported in field calibration results for tipping bucket type rain gauges is the date and time of calibration, reference intensity in mm/hour (Iref), average intensity (IUUT) in measured mm/hour by the tipping bucket rain gauge during calibration.

$$I_{UUT} = \frac{1}{N}\sum_{j=1}^{N} I_{1min}^{j} \tag{1}$$

The relative percent error of the average intensity is calculated as follows:

$$RE_{avgI} = 100\left(\frac{I_{UUT}-I_{ref}}{I_{ref}}\right) \tag{2}$$

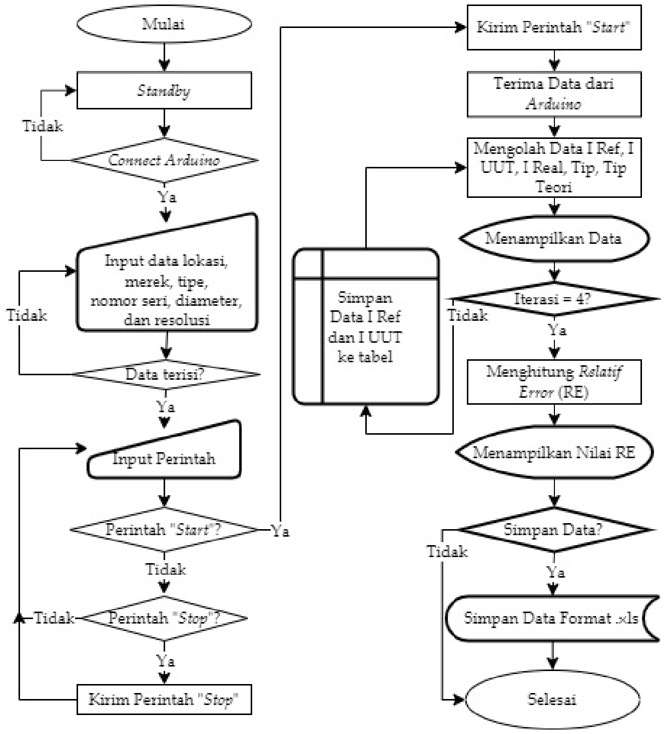


Figure 3. Flow Diagram in Applications

Tool Design

The calibrator tube is a cylindrical tube with 2 water channels (outlet and inlet) and 2 air channels (channel 1 and channel 2). The following is a 3D design of the calibrator tube and its parts.

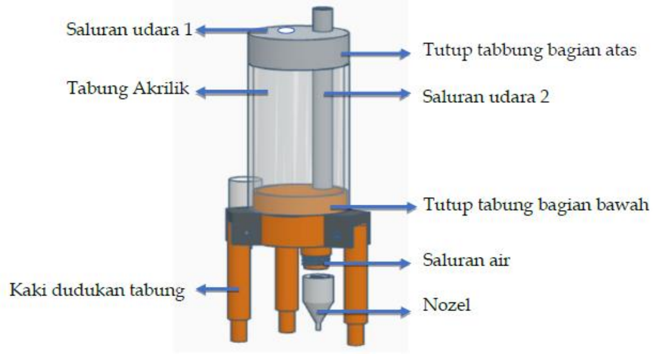
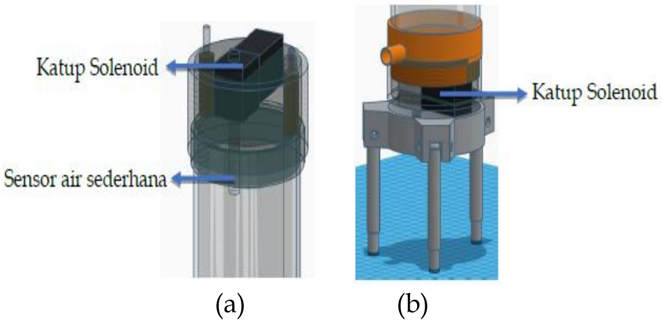


Figure 4. Calibrator Tube

The stand leg functions as a support for the calibrator unit when used for calibration. The legs of the stand are 3 solid cylinders connected to a stand with a length of ± 15 cm, and can be positioned horizontally and vertically. The placement of electronic components in the calibrator tube is shown in Figure 3 and Figure 4. The solenoid valve in Figure 3 (a) functions to remove air during the water filling process, while the solenoid valve in Figure 3 (b) functions as a water flow regulator. Apart from that, there is an air intake pipe which will suck in outside air when the water in the tube flows out. Using this pipe will provide a constant flow effect.



(a) (b)

Figure 5. (a) Solenoid valve and simple water sensor on the top cover, (b) Solenoid valve on the bottom of the tube

The volume measuring system consists of a simple water sensor based on the IC LM393 (Figure 5 (a)) and one load cell that can measure mass up to 5 kg. A simple water sensor is a component for detecting the maximum limit of water volume in the tube, while the load cell functions to measure the mass of water during the flow process until the water reaches the minimum limit of water volume based on the reduced water mass. The design for placing the load cell sensor can be seen in Figure 6. The microcontroller box and other components will be made separately. There are several components in the microcontroller box, including the microcontroller and 12 V DC pump.

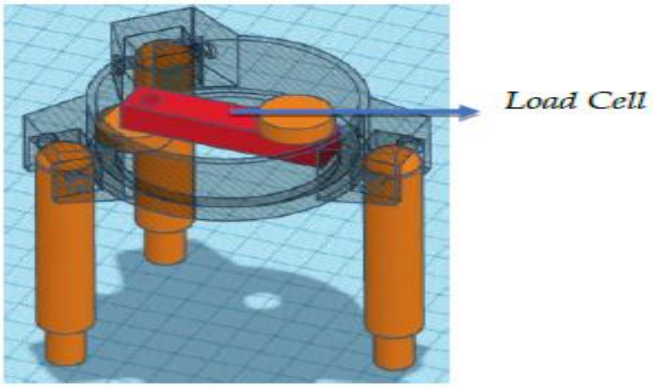


Figure 6. Load cell on tube holder

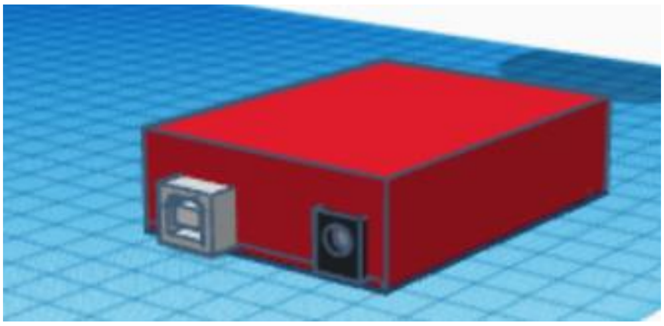


Figure 7. Microcontroller box

Results and Discussion

Hardware

Several hardware parts are printed using a three-dimensional printer to realize the planned design. Meanwhile, the electronic components used form a water flow system, measuring water volume, measuring time, and measuring the number of calibrated rain gauge tips (Dervos & Baltas, 2024; Lanza et al., 2021). The tube cover functions as a space for placing the water sensor, air solenoid valve and wiring.


Figure 8. Assembled calibrator tube

From the bottom view you can see the water sensor which will provide a full water indicator when the water surface has reached the two conductors. Apart from that, there is a pipe to stabilize the water flow during the draining process. There is also an air outlet hole which functions to release air during the water filling process, the channel of which is regulated by a solenoid valve. There is a solenoid valve and its circuit which is connected to the air hole.

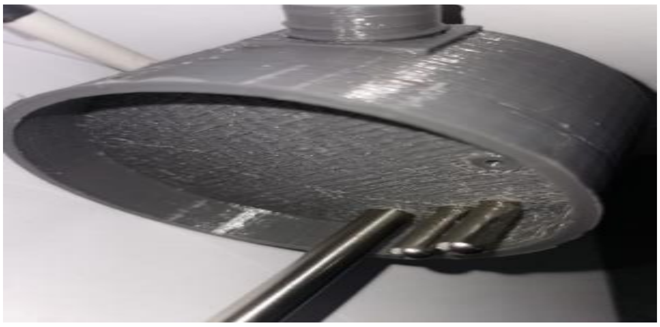


Figure 9. Tube cover, air channel and water sensor


Figure 10. Solenoid valve for air duct

The bottom of the lid provides space to place the solenoid valve and load cell module (Lau et al., 2019). The tube holder is divided into two parts, namely the foot of the stand and the main part of the stand which functions as a space for placing the load cell. The first part is 3 tube feet to support the calibrator tube on the rain measuring funnel.

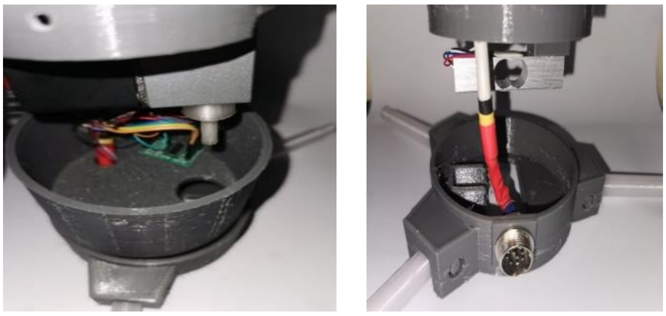

(a) (b)

Figure 11. (a) Water flow control solenoid valve, (b) Placement of the load cell as a support for the tube


Figure 12. Placement of electronic components in the microcontroller box

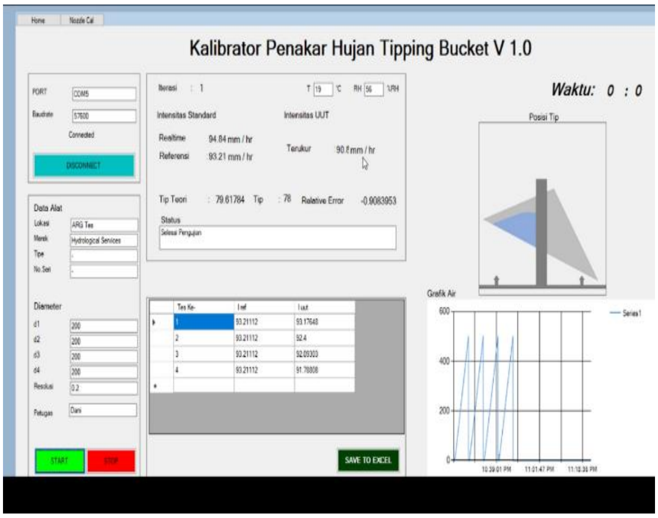
The microcontroller box and pump are separate from the calibrator tube (Purba et al., 2023; Brown et al., 2020; Tuncay et al., 2020). The box is connected to a hose for water flow and cables to control giving commands and receiving responses from sensors. Between the microcontroller and the pump there is a partition which functions as a protector for the microcontroller when there is a leak in the water channel in the pump (Rapeaux & Constandinou, 2020). The box is equipped with a cable port for the electronic components in the calibrator tube, and a port for a hose from the water source, as well as a hose to drain water into the calibrator tube. Apart from that, there is also a switch to turn on and turn off the electronic system on the tool.

Apart from DC pumps and solenoid valves, there are supporting components for the water flow system, namely certain types of hoses and ports. In this study, a hose with an inner diameter of 5 mm and a thickness of 3 mm, pneumatic fittings and a one-way valve were used. The hose functions as a water conductor from the initial storage container to the calibrator tube. Pneumatic fittings are used as ports for hoses at each connection, both connections to pumps and calibrator tubes. The one-way valve is used to stop the flow from the calibrator tube back to the pump when the pump stops.

Figure 13. Prototype of Portable Automatic Calibrator for Tipping Bucket Rain Gauge

User Interface (UI)

Apart from hardware, there is software used in this research, the most significant of which is the use of Visual Studio software. This software functions to create applications that function as UI on this system. Apart from that, the function of this application is to process calibration data and as a means of monitoring calibrator performance. UI is a visual display of tools that connect the product with the user. The UI functions to give commands to the hardware, calculate the calibration results of the tipping bucket rain gauge, and display the calibration results. The data sent by the microcontroller is processed based on the program to produce Realtime Intensity, Reference Intensity, Measured Intensity and Relative Error values. The calibrated parameter is rain intensity (mm/hour) with the calculation of the relative error value (%) produced by the calibrated rain gauge.



PORT COM5
Baudrate 57600
Connected

Data Alat
Lokasi ARG Tes
Merek Hydrological Services
Tipe -
No.Seri -

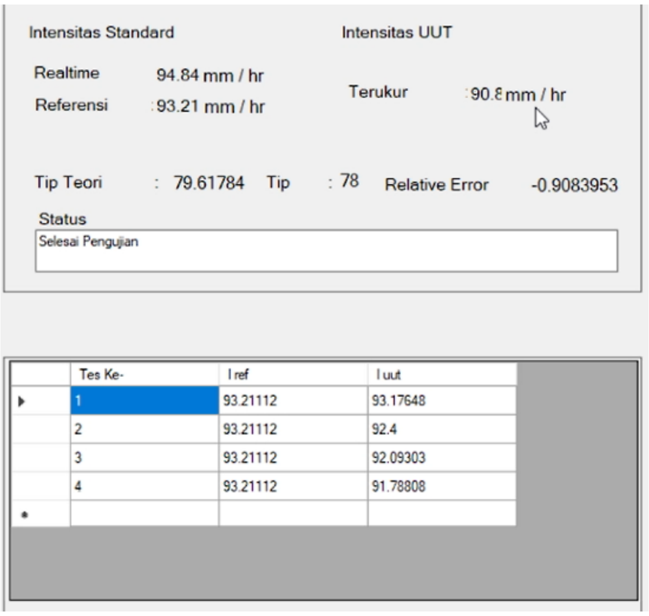
Diameter
d1 200
d2 200
d3 200
d4 200
Resolusi 0.2
Petugas Dani

Iterasi : 1
T 19 °C RH 56 %RH
Waktu: 0 : 0

Intensitas Standard
Realtime 94.84 mm / hr
Referensi 93.21 mm / hr
Intensitas UUT
Terukur 90.8 mm / hr
Tip Teori : 79.61784 Tip : 78 Relative Error -0.9083953
Status
Selesai Pengujian

Tes Ke-	I ref	I uut
1	93.21112	93.17648
2	93.21112	92.4
3	93.21112	92.09303
4	93.21112	91.78808

Figure 14. User Interface



Intensitas Standard
Realtime 94.84 mm / hr
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Terukur :90.8 mm / hr
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Selesai Pengujian

Tes Ke-	I ref	I uut
1	93.21112	93.17648
2	93.21112	92.4
3	93.21112	92.09303
4	93.21112	91.78808

Figure 15. Rain gauge calibration results on the UI

The nozzle discharge value is set at 0.81 ml/s. The diameter data is processed into an area value (A) to convert the nozzle discharge value into a reference intensity value (Iref) for the calibrator. The nozzle discharge is determined based on experiments carried out after the volume and stopwatch calibration stages. The following is a manual calculation for the Iref value.

$$
\begin{aligned}
I_{ref} &= \frac{Q}{A} \\
&= \frac{0{,}813\ {}^{ml}/_{s}}{314\ cm^2} \\
&= 0{,}002589\ {}^{cm}/_{s} \\
&= 93{,}21\ {}^{mm}/_{jam}
\end{aligned}
\tag{3}
$$

Meanwhile, the UUT rain intensity value varies at each iteration. In the 1st iteration with a total of 77 tips and a draining time of 595 seconds, the UUT rain intensity value was 93.176 mm/hour. This value is obtained from:

$$
\begin{aligned}
I_{UUT} = \frac{Tip \times res}{t} = \frac{77 \times 0{,}2}{595\ s} &= 0{,}02588\ {}^{mm}/_{s} \\
&= 93{,}176\ {}^{mm}/_{jam}
\end{aligned}
\tag{4}
$$

In iterations 2, 3, and 4, there were 77 tips each, with times of 595s, 600s, 602s, and 604s, resulting in UUT rain intensity values of 92.40 mm/hour, 92.09 mm/hour, and 91, respectively. 7 mm/hour. So, the average value of I UUT is obtained:

$$
\overline{I_{UUT}} = 92{,}36\ {}^{mm}/_{jam}
\tag{5}
$$

The following table is calculated manually to compare with the calculations contained in the UI.

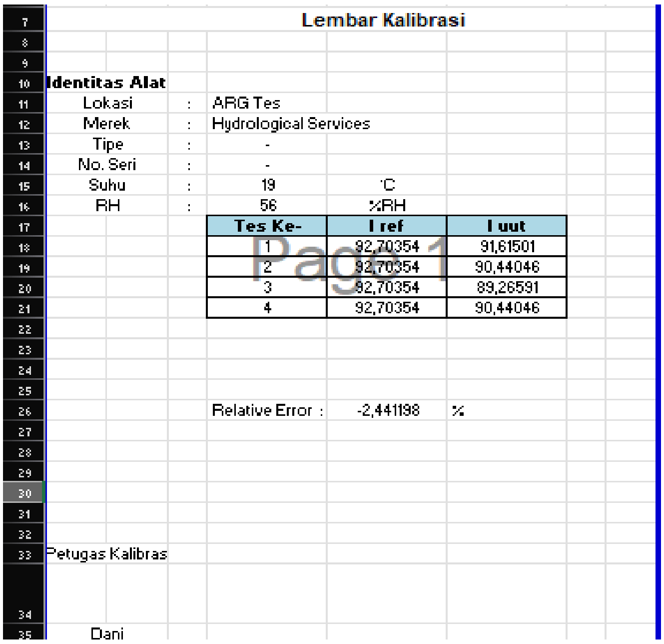
Table 1. Calibration data calculated manually

Test To	I_{ref}	Tip amount	Time (s)	I_{uut} (mm/hour)	Deviation (mm/hour)
1	93.20	77	595	93.20	-0.03
2	93.20	77	600	92.40	-0.81
3	93.20	77	602	92.10	-1.12
4	93.20	77	604	91.80	-1.42
Average	93.20	77	600	92.40	-0.85

Each calibration process has 4 iterations which take place continuously. Each iteration takes into account Iref, number of tips, and duration, resulting in an IUUT value. The deviation values from Iref and IUUT are calculated, then averaged and converted into relative error values in % units. So, to calculate the relative error value, it is:

$$
\begin{aligned}
RE_{avgI} &= 100\left(\frac{\overline{I_{UUT}}-I_{ref}}{I_{ref}}\right)\% \\
&= 100\left(\frac{92{,}36\ {}^{mm}/_{jam} - 93{,}21\ {}^{mm}/_{Hour}}{93{,}2\ {}^{mm}/_{\square}haour}\right)\% \\
&= 100\left(\frac{\mathbf{-0{,}85}\,{}^{\boldsymbol{mm}}/_{\boldsymbol{hour}}}{93{,}2\,{}^{mm}/_{hour}}\right) = -0{,}91\ \% \qquad (6)
\end{aligned}
$$

Apart from being displayed on the UI, rain gauge calibration data can be exported and downloaded in .xls format. So that the data can be printed into hardcopy. The following is an example of downloading calibration data during an experiment.



Lembar Kalibrasi

Identitas Alat

Lokasi : ARG Tes
Merek : Hydrological Services
Tipe : -
No. Seri : -
Suhu : 19 'C
RH : 56 %RH

Tes Ke-	I ref	I uut
1	92,70354	91,61501
2	92,70354	90,44046
3	92,70354	89,26591
4	92,70354	90,44046

Relative Error : -2,441198 %

Petugas Kalibras

Dani

Figure 17. Example of calibration results in .xls format

The drawback of the software is that it still requires additional information on the exported calibration results, such as the identity of the laboratory, the front page of the calibration certificate which contains the certificate header, the identity of the tool being calibrated and validation from the laboratory that issued the calibration certificate. The advantage lies in the tipping bucket rain gauge calibration method contained in the software (Liao et al., 2021; Choi et al., 2023). In a similar study, the parameter calibrated was the amount of rainfall in mm units (Reynolds et al., 2017; Islam et al., 2023; Nikahd et al., 2016; Yang et al., 2021). Meanwhile, in this research product, the calibrated parameter is rain intensity in units of mm/hour, in accordance with WMO No.8.

Conclusion

The tipping bucket rain measuring calibrator consists of hardware that functions as a calibration medium and an application that functions as data processing, data presentation and data storage. dimensions. The calibrator can perform 4 (four) retrievals of tipping bucket rain gauge calibration data. The rain gauge calibration method recommended in WMO No. 8 can be applied to a tipping bucket rain gauge calibrator with rain intensity parameters (mm/hour), and produces an output value in the form of a relative error of the rain gauge calibrated in % units. However, this research still requires further refinement to complete and improve overall system performance.

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Author Contributions
Conceptualization, D.Z.R. and BSU; methodology, DZR; software, BSU; validation, D.Z.R. and BSU; formal analysis, DZR; investigation, DZR; resource, DZR; data curation, DZR; writing—preparation of original draft, D.Z.R.; writing—review and editing, D.Z.R., J., S., and BSU; visualization, BSU; supervision, J. and S.; project administration, DZR; funding acquisition, D.Z.R. All authors have read and approved the published version of the manuscript.

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Conflict of Interest
We declare that there are no conflicts of interest with any financial, personal, or other relationships with other people or organizations related to the material discussed in the manuscript.

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