REAL-TIME WATER LEVEL MONITORING USING LOW-COST GNSS RECEIVER

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ABSTRACT:

Developing an accurate water level monitoring system is one of the measures to mitigate the effects of water-related hazards such as river flooding. While current monitoring systems in the country are efficient in terms of accurate and immediate data delivery, these systems can be costly. This study assesses the Global Navigation Satellite System (GNSS) performance of low-cost receiver systems for water level monitoring using real-time kinematic (RTK) solution. A total of 10 days' valid observation were analyzed to compare the two base-rover receiver setups: 1) low-cost base to low-cost rover (LC-LC) and 2) survey-grade base to low-cost rover (SG-LC) grounded on accuracy, integrity, continuity, availability, and cost. Accuracy results show LC-LC=5.81 cm and SG-LC=5.37 cm mean difference of RTK from in-situ readings. In terms of RTK and post-processing kinematic (PPK) difference for integrity criterion, the RTK SG-LC setup has a lower range of RMS of 0.86 to 1.94 cm versus LC-LC setup of 1.19 to 2.28 cm. For the continuity criterion, the average fixed solutions percentage for the LC-LC setup: RTK=91.43%, PPK=92.92%, whereas for the SG-LC: RTK=95.51%, PPK=98.39%. On availability, the number of valid satellites (NSat) and position dilution of precision (PDOP) of RTK and PPK solutions for each setup are LC-LC: RTK=11, PPK=23, PDOP=1.0 and SG-LC: RTK=11, PPK=24, PDOP=1.9. Lastly, in terms of costing, LC-LC costs Php 58,340 while SG-LC costs Php 1,279,645. Overall, the parity of LC-LC with SG-LC in terms of the five criteria suggests viability of using LC-LC for accurate real-time water level monitoring.

1. INTRODUCTION

1.1 Background of the Study

In recent years, the consequences of climate change have caused the weather to become unpredictable and severe, especially in midlatitude regions. Temperature, wind, and rainfall forecasts become unreliable despite using up-to-date weather prediction models (Garthwaite, 2021). This uncertainty poses a major challenge in countries prone to extreme weather events such as the Philippines as it translates to having less time for preparation and mobilization. More so, national warning centers often neglect registering recurring events which leads to inefficient and limited coping strategies (Global Initiative on Disaster Risk Management, n.d.). As a result, significant economic and social progress reverts, sometimes worsening a country's prospects for development.

One of the solutions in mitigating the effects of water related hazards is developing an accurate water level monitoring system. Monitoring systems prepared by the Department of Science and Technology (DOST) such as the Automated Rain Gauges (ARG) and Automated Water Level Sensors (AWLS) have been installed in flood-prone areas in 2012 as part of its improved disaster prevention and mitigation strategies. While these systems are efficient in terms of accurate and immediate data delivery, they can be quite uneconomical especially for LGUs with limited budget. Thus, it is paramount that modern techniques such as low-cost early-warning systems with real-time data delivery capability are incorporated in water level observations. It is through these approaches that storm-surges are accurately and immediately forecasted to local communities which will consequently improve emergency response and management.

A study on GNSS using post processed-kinematic (PPK) data acquisition by the Coastal Sea Level Rise (CSLR)-Phil team headed by Dr. Rosalie Reyes in coordination with the GNSS Laboratory of the University of Tokyo has been evaluated for sea level rise monitoring. PPK solutions from a GNSS tide gauge float and buoy have demonstrated an RMSE ranging from 3cm to 9cm, thus, concluding a viable technique for water level monitoring. It was recommended, however, to do a similar study in real-time kinematics (RTK) to explore the viability of monitoring the water level in real-time.

Although low-cost GNSS receivers have been tested for sea level rise studies using PPK solutions, there is still a need to further evaluate its performance in a base-rover configuration with RTK processing for water level monitoring purposes. Investigating affordable alternatives to expensive GNSS survey-grade instruments while providing real-time data delivery as well as remote accessibility will aid developing and flood-risk countries like the Philippines.

1.2 Research Objectives

The main objective of this study is to evaluate the performance of the low-cost GNSS receiver for water level monitoring using a single baseline RTK solution. The specific objectives are:

i. Compare the performance of two RTK base-rover receiver configurations: 1) Low-cost base to Low-cost rover receiver configuration (LC-LC); and 2) Survey-grade base to Low-cost rover receiver (SG-LC) configuration.

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ii. Compare the results of the suggested systems with post-processed kinematic solutions and in-situ readings from a water level staff.
iii. Evaluate the real-time kinematic GNSS data processing capability and remote accessibility of the low-cost GNSS receiver system.

1.3 Scope and Limitations

The low-cost GNSS receiver utilized is the u-blox ZED F9P multi-frequency receiver while the survey-grade GNSS receiver is the Trimble NetR9 reference receiver as base station.

Both RTK and PPK solutions were evaluated using readings of water level from zero-level staff installed in the rover station. The Zero Staff (0) reading was assigned an equivalent height above mean sea level (MSL). GPS and GLONASS were the only satellite systems utilized in processing the solutions because the RTCM corrections in RTK of ZED F9P and NetR9 are limited to these satellite systems. The latency of transmitting RTK solutions was also not considered during the data validation from in-situ measurements. Air draft inside and outside the rover receiver was assumed to be equal and constant, hence, differences in the measurements from the tide staff as well as the PPP solutions were disregarded.

2. METHOD

2.1 Study Area

The lagoon system near the College of Fine Arts (CFA) at the University of the Philippines, Diliman campus was the site for the rover receiver. A solar power system was optimally utilized as the power source of the rover receiver. The terrain allowed for the establishment of a semi-permanent benchmark: the basis of the geographic coordinates of the rover station.

2.2 Equipment

The receivers used for the low-cost base and rover systems were equipped with the u-blox C099-F9P application board which contained the ZED-F9P chip. It was a multi-frequency and multi-constellation GNSS receiver capable of acquiring GNSS signals in the lower and upper L-band (L1C/A, L1OF, E1, B11, L2C, L2OF, E5b, B21). The u-blox module can operate in RTK and RTN (Real-Time Network) modes with a high-frequency measurement rate of up to 20-Hz and a positioning accuracy of 1 cm + 1-ppm CEP within the 20-km baseline limit. Multipath signals were expected to be mitigated and discarded due to the receiver's anti-jamming and anti-spoofing algorithms (Sana et al., 2022). While capable of multi-frequency and multi-GNSS observations, the u-blox ZED-F9P had limited GNSS signal reception (Fredeluces et al., 2020). RTCM corrections in RTK mode can be transmitted between the base and rover through various modes such as wired-transfer, Bluetooth, and Wi-Fi, configured through the u-center GNSS evaluation software developed by the company. A low-cost patch antenna ANN-MB-00 included in the standard package of the module was utilized for the study. This was a Right-Hand Circular Polarized (RHCP) antenna that can receive dual bands (L1 and L2/E5b/B21).

For the remote PCs, a Beelink minicomputer was also integrated into the system as the remote PC for the rover. It was a Windows computer equipped with an Intel Celeron N5095 processor, 8GB of random-access memory, and 512GB of storage. To facilitate wireless access and data transfer, a pocket Wi-Fi was connected to Beelink. On the other hand, a Legion laptop computer served as the remote PC for the base station and real-time data collection, referred from hereon as Desktop PC. A Windows computer as well, its specifications included an Intel Core i7 processor, 32GB of random-access memory, and 952GB of storage. It was connected to a Wi-Fi access point available at the GNSS laboratory. Both computers were capable of efficiently running multiple instances of different RTKLIB modules and/or u-center simultaneously.

To assemble the low-cost GNSS rover for monitoring the water level in the study area, a PVC pipe 6” in diameter, an aluminum pole 1” in diameter, and a floater made from a plastic jar were utilized. These components were placed in custom-made housing designed to prevent exposure to potential physical disturbances (e.g., sunlight, weather, and unwarranted tampering). Additionally, a solar power system composed of solar panels and series-connected dry cells regulated by a solar controller was the main power source of the system. Figure 3.3 shows the individual components of the rover setup.

2.3 Receiver Stations Setup

Figure 1 shows the actual setup at the lagoon featuring the patch antenna and the solar panels. On the other hand, the C099-F9P application board, Beelink minicomputer, dry cell, and pocket Wi-Fi were placed in the housing. After the hardware setup, the Beelink PC was configured for remote access using Chrome Remote Desktop.

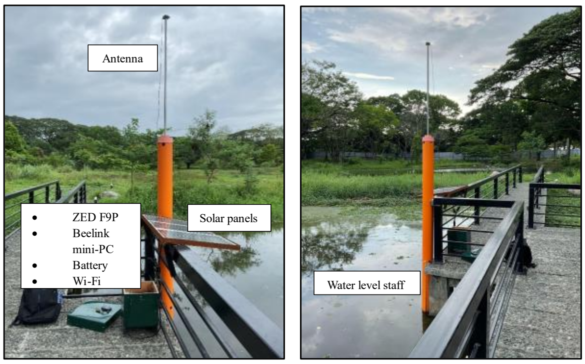

Figure 1. Low-cost GNSS rover receiver setup.

Meanwhile, the base stations u-blox and NetR9 receivers were installed at a GNSS laboratory in Melchor Hall. The positions of the receivers were defined by the published coordinates of the UoP station.

2.4 Data Collection & Processing

The diagram in Figure 2 details the workflow involving the file outputs during and after GNSS observation in RTK data processing. Note that identical procedures were performed during PPK in both setups, as shown in Figure 3. In RTK processing, the prerequisite was the real-time data streams of both the rover and base stations. Once the RTKNAVI was up and running, the raw solution files were automatically saved in the local storage of the desktop PC. As for the PPK processing, raw measurements of the rover and base stations that were recorded by RTKNAVI during real-time observations were converted to RINEX 3.03 files using RTKCONV, yielding .obs, and .nav files. These served as input files in RTKPOST to produce the PPK solutions in .pos format.

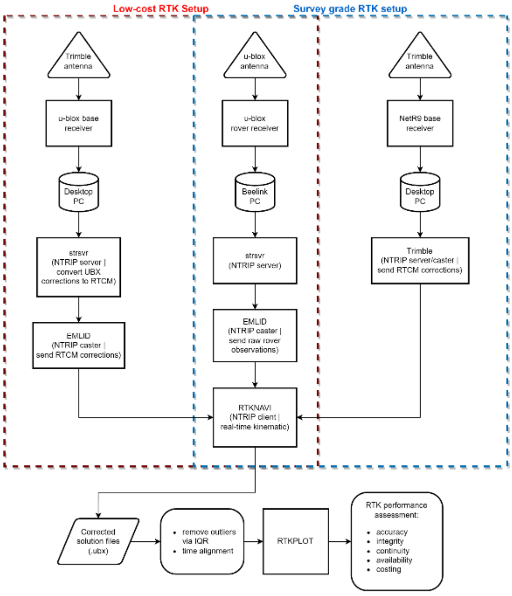

Figure 2. RTK process for LC-LC and SG-LC.

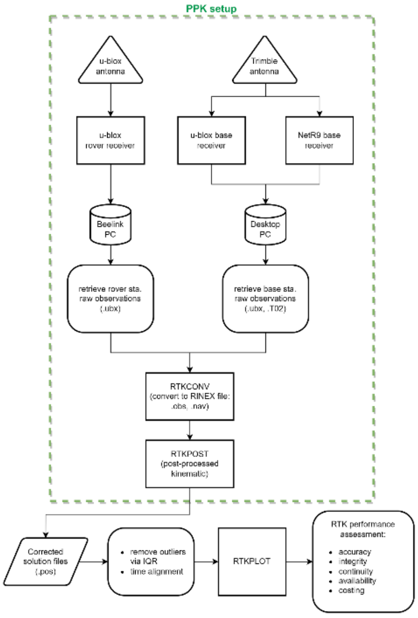

Figure 3. PPK process for LC-LC and SG-LC.

3. RESULTS AND DISCUSSION

3.1 Observation Period

The observation period was conducted in April (LC-LC) and May (SG-LC) 2023. A total of 10 days' worth of data valid for analysis were chosen for each of the LC-LC and SG-LC setups. One of the factors considered to establish the validity of a day's observation includes the availability of a .nav file from the rover's raw observations. An additional consideration is the number of fixed solutions in an observation, where there should be at least a length of 3 hours to achieve a cm-level of RMS errors (Satchet et. al., 2020). Consequently, the same hours were set as the minimum required duration of overlap between the RTK and PPK solutions.

3.2 Performance/Comparative Analysis

3.2.1 Accuracy: The first criterion is the data accuracy, determined by comparing the RTK solutions of the low-cost and survey grade setups against their respective water level readings based on the elevation of the 0-m level staff. Only RTK measurements of the setups were compared against the field readings as it derived the reliability of the system in real-time correspondence to ground truth data, which is one of the main objectives of this study. Deriving conclusions about the capacity of PPK of both setups in corresponding to ground truth is not within the scope and focus of this study. The analysis required a per-point comparison of the readings against the recorded RTK observations, thus time-alignment between the two was imperative.

Only those with corresponding fixed solutions and non-outliers were matched. Table 1 shows the in-situ water level and corresponding RTK-derived water level based on the 0-m level staff for five days within the LC-LC setup operational period, with the difference visualized in Figure 4. In LC-LC setup, an average difference of 5.81 cm was observed between in-situ water level and RTK water level. This sub-decimeter level of accuracy of the LC-LC RTK indicates a desirable correspondence with the observations of the in-situ water level. Based on these results, the low-cost setup was able to achieve survey-grade accuracy of real-time water level monitoring. Meanwhile, Table 2 and Figure 5 show the five-day in-situ water level vs. RTK-derived water level based on the 0-m level staff for the SG-LC RTK setup. An average of 5.37 cm difference was observed between the two quantities, which also suggests an expected sub-decimeter level of accuracy. The source of these differences can be attributed to the assumption that the air draft inside the pipe was equal to that of the outside, which might have left an unaccounted length during the measurement of the constant antenna height.

Day	In-situ Water level	RTK-derived Water Level
April 18, 2023	13.50	18.66
April 20, 2023	13.00	18.76
April 25, 2023	13.00	20.35
April 27, 2023	13.50	20.94
April 28, 2023	13.50	16.83

Table 1. Comparison of in-situ water level readings and low-cost RTK-derived water level above 0-level staff (unit: cm).

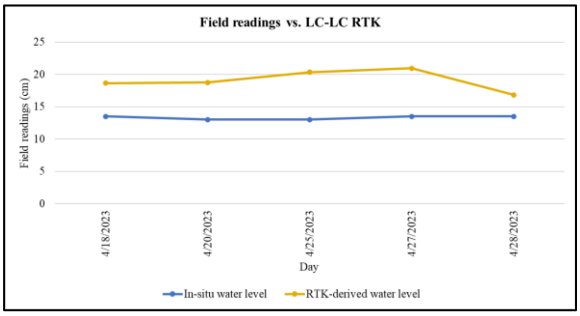

Figure 4. Comparison of in-situ water level readings vs. RTK derived water level of LC-LC setup.

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Day	In-situ Water level	RTK-derived Water Level
May 06, 2023	13.50	18.90
May 08, 2023	13.00	20.12
May 10, 2023	18.50	25.88
May 15, 2023	15.00	19.28
May 17, 2023	19.00	21.68

Table 3. Comparison of in-situ water level readings and low-cost RTK-derived water level above 0-level staff (unit: cm).

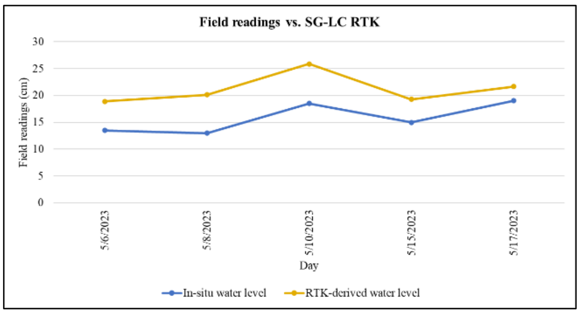

Figure 5. Comparison of in-situ water level readings vs. RTK derived water level in SG-LC setup.

It can be observed that the difference between the in-situ and RTK-derived water level of April 28 in LC and May 17 in SG were noticeably smaller: 3.33 cm and 2.68 cm, respectively. The deviation from the trend of the April 28 measurement could possibly be attributed to the relatively low number of valid satellites which was 11 at the specific time of comparison, below the average Nsat which was 12.5 for April 28. On the other hand, May 17 comparison displayed similar trend. However, the source of this difference may be attributed to the cycle slips that occurred shortly before and after the time of comparison.

3.2.2 Integrity: The second criterion was system integrity, assessed by comparing each setup's RTK against the PPK statistics and thereafter comparing the setups' RTK-PPK statistics. Specifically, the RMS was the focus of comparison post-tabulation. When interpreting the results, awareness of the origin coordinates is imperative. Similar to the trend observations, the RTK and PPK that were applied with z-pump were used here to allow for correct inter-setup comparison. On the other hand, for the correct intra-setup comparison of RTK and PPK, mean ellipsoidal height per day served as vertical datum.

Shown in Table 3 are the maximum and minimum RMS of the low-cost and survey grade, in RTK and PPK of the U-D direction. For the inter-setup comparison: it can be observed that the RTK and PPK RMS values of LC-LC setup are better than that of the SG-LC setup, but this difference is in mm-level. A possible explanation for the difference is the lower DOP values of LC-LC observations, which will be discussed in the proceeding section. Based on these results, LC-LC setup achieved sub-decimeter level of precision comparable with SG-LC setup.

	RMS U-D Direction			
	LC-LC		SG-LC	
	RTK	PPK	RTK	PPK
MIN	1.68	1.31	1.59	1.35
MAX	2.74	1.96	3.26	3.18
MEAN	2.18	1.59	2.14	1.75

Table 2. RMS summary in the U-D direction of LC-LC and SG-LC setups for intra-setup comparison (unit: cm).

Furthermore, in terms of comparison between RTK and PPK in both setups, the PPK solutions have a lower range of RMS indicating greater precision than RTK solutions. However, sub-centimeter RMS differences in the RTK and PPK of both setups imply that the RTK and PPK of each setup are similar. This similarity is depicted in Figure 6 for LC-LC and Figure 7 for SG-LC. This is further supported by the RMS value of RTK-PPK difference: while the LC-LC has a higher range of 1.19 – 2.28 cm versus SG-LC's 0.86 - 1.94 cm, indicating that the RTK solutions of the SG-LC setup are more on par with its PPK solutions, the difference is only in mm-level.

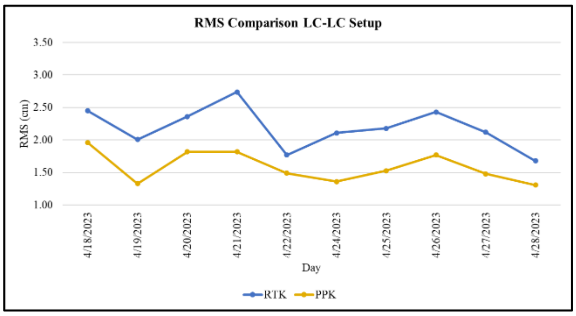

Figure 6. Plotted RMS comparison of LC-LC setup.

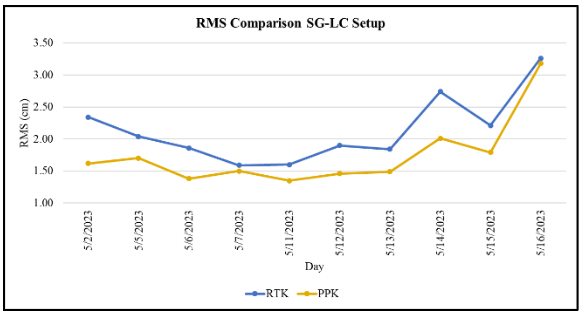

Figure 7. Plotted RMS comparison of SG-LC setup.

3.2.3 Continuity: The percentage of ambiguity-fixed solutions relative to the rest of the solutions per day was analyzed for low-cost and survey grade. Invalid values of height data were excluded in percentage calculation.

During the LC-LC setup, the minimum and maximum percentage of the fixed solution in the RTK solution was found with values of 68.95% and 99.57%, respectively. In the same setup, fixed solutions were consistently observed in PPK (minimum=83.35%, maximum=99.22%). The SG-LC setup showed a similar observation wherein the minimum percentage is found in the RTK solution and consistent percentage values in the PPK solution. The minimum and maximum percentage values for SG-LC setup in the two solutions are: RTK: minimum=87.40%, maximum=98.34%; PPK: minimum=92.87%, maximum=99.92%.

It is expected that PPK solutions result in a higher percentage of fixed solutions due to the difference in the solution algorithms it offers compared to RTK (Knight et al., 2021). A forward algorithm, which is absent during RTK processing, was applied in PPK mode allowing for more accurate timing corrections of an overall solution. However, this does not imply a superior continuity evaluation compared with the RTK solution since the average percentage from both setups has a 2.19% difference, i.e., 93.47% and 95.66% average fixed solutions in RTK and PPK, respectively.

When comparing the continuity of LC-LC and SG-LC setup, higher percentage values were observed in the latter. The average percentage of fixed solutions for LC-LC setup are 91.43% and 92.92%, in RTK and PPK respectively. Whereas for SG-LC setup the values are 95.51% and 98.39%, in RTK and PPK respectively. Possible reasons for the lower number of fixed solutions in LC-LC are the differences in signal processing capacity of the base stations and more NTRIP disconnection. Probable sources of the lower number of fixed solutions for LC-LC include differences in signal processing capacity of the base stations.

3.2.4 Availability: The criteria of availability were assessed using the number of valid satellites tracked during the water level monitoring observations. According to Atiz et al. (2022), RTK measurements are generally derived from GPS and GLONASS constellations leading to delimitations in accuracy due to satellite geometry restrictions. It was observed during RTK that the base stations, both ZED F9P and NetR9, only used GPS and GLONASS signals as valid sources of measurements, while all GNSS satellite systems are utilized during post-processing.

In both setups, a higher number of NSat was observed for post-processed solutions since solution algorithms of PPK account for other timing corrections from satellites are not accounted for in RTK (Knight et al., 2021). Moreso, signal transmission from the GPS and GLONASS constellations to the rover receiver during RTK was affected by environmental limitations. Although the rover was installed in an open sky environment, a tree nearby was located approximately at the North-West plane of the setup. This reflects the deterioration of signal quality most likely caused by the tree reducing the number of valid satellites for real-time solutions.

The overall NSat average of RTK and PPK for each setup are as follows: a) NSat in LC-LC: RTK=11.35 and PPK=23.30; b) NSat in SG-LC: RTK=11; PPK=23.85. There is minimal difference between the average NSat of the two setups despite the variation in the hardware specifications of the type of base receiver used, i.e., F9P and NetR9 have maximum available receiver channels of 184 and 440, respectively (Fredeluces & Lagura, 2020). One probable cause for this observation is that the F9P and NetR9 are connected to the survey-grade antenna in the reference station UoP via a splitter, thus, receiving similar signals during data acquisition.

The number of satellites observed consequently affects the geometry of the GNSS constellation. Satellite geometry is reflected in the number of the DOP categorized into geometric DOP (GDOP) and position DOP (PDOP) within the .obs file of the base station. The GDOP value shows how equally spaced the satellite geometry is. The PDOP value, on the other hand, exhibits the accuracy of the satellite geometry and is composed of two components namely, horizontal DOP (HDOP) and vertical DOP (VDOP). In most scenarios, large values are seen in VDOP than in HDOP since there are only a limited number of satellites deployed higher in the sky (Tahsin et al., 2015).

DOP values during the low-cost setup demonstrate as ideal, whereas it was excellent during the survey-grade setup based on the ratings cited in Tahsin et al. (2015). As expected, VDOP values are greater than HDOP in both setups, however, a greater difference in these values is prominent in the survey-grade setup. The cut-off elevation angle of the instrument system also affects DOP values (Tahsin et al. 2015). This observation implies that there might be a need to reconfigure NetR9 reception settings or adjust the cut-off elevation angle of the instrument settings to improve DOP.

3.2.5 Costing: The main equipment utilized for the comparative GNSS performance analysis of low-cost GNSS receivers are two u-blox Zed F9P base and rover receivers, and Trimble NetR9 base receiver. The antenna for the Zed F9P rover was the provided patch antenna from the u-blox kit while the base receivers were connected to the provided Trimble survey-grade antenna via GNSS splitter. It is important to highlight the RTK accuracy of the low-cost receiver applicable for many positioning applications. Circular Error of Probability (CEP) is defined as circular radius with the receiver position as the center in which GNSS measurements are contained 50% of the time (Webb, 2012), and in terms of horizontal and vertical accuracy, ZED F9P is reported with 10mm + 1ppm CEP, a sub-centimeter accuracy. The cost of each setup, at the time of writing, containing the rover receiver and base receiver systems are laid out in Table 4.

	Component	**LC-LC Setup**	**SG-LC Setup**
Rover Receiver System	u-blox Zed-F9P	18,000	18,000
	Beelink DDR4 8GB+512GB SSD	10,000	10,000
	Solar Panel	4,500	4,500
	Solar Controller	140	140
	Lifepo4 Prismatic Solar Battery	5,000	5,000
	Pocket Wi-Fi	700	700
	Housing and PVC Pipe	2,000	2,000
Base Receiver System	u-blox Zed-F9P	18,000	--------
	Trimble NetR9 reference Receiver	--------	1,117,030
	Zephyr Geodetic Antenna	--------	122,275
	Total Cost	**58,340**	**1,279,645**

Table 4. Price comparison of LC-LC and SG-LC setups (in Philippine peso).

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

The 10-days' worth of water level measurements collected for the LC-LC and SG-LC setups were analyzed using RTK and PPK solutions. To evaluate the performance of the setups and solution types, the researchers adapted the four navigation criteria namely accuracy, integrity, continuity, and availability as parameters. The results of the evaluation per criteria are as follows:

Accuracy: The LC-LC setup was able to achieve sub-decimeter accuracy of real-time water level monitoring. An average difference of 5.81 cm was observed between in-situ water level measurements and RTK derived water level during the LC-LC setup, whereas in SG-LC setup 5.37 cm of average difference was observed. Despite the non-overlap of point solutions with the field readings, the two variables demonstrate a similar trend when plotted against each other. This indicates that the water level based on the 0-level staff from the RTK solutions in both setups is consistent with in- situ data.

Integrity: RTK and PPK RMS values of LC-LC setup demonstrated an mm-level difference compared with the SG-LC setup, i.e., 0.05 mm and 0.16 mm difference in RTK and PPK, respectively. Furthermore, the RTK and PPK RMS values of LC-LC setup are better than that of the SG-LC setup with mm differences.

Continuity: PPK was able to perform more continuous observation than the RTK mode in both setups. However, this difference was considered insignificant as there is a 2.19% difference in the average percentage of ambiguity fixed solutions for RTK and PPK with the latter solutions having a higher percentage. More importantly, LC-LC was able to provide continuous viable solutions similar to SG-LC.

Availability: There is minimal difference between the average NSat of the LC and SG setups despite the variation in the hardware specifications of the type of base receiver used. Additionally, a higher number of satellite systems were tracked and used as valid when solutions were processed in PPK than in RTK, as expected. Meanwhile, the DOP values during the LC-LC setup had ratings better than those in the SG-LC setup.

Based on the four criteria, the RTK and PPK solutions of the LC-LC setup are comparable and exhibited consistency in correction capacity with SG-LC setup while being more economical. RTK solutions from the two setups are also reliable when compared to ground truth measurements. Moreso, the LC-LC setup costs 22 times less than the SG-LC setup, thus, is a more economical choice for water level monitoring systems.

Utilizing NTRIP connection between base and rover receivers for the two setups have made real-time data delivery and remote accessibility possible. This suggests that this study's low-cost GNSS setup is viable for accurate real-time water level monitoring and is an alternative to expensive or high precision survey-grade GNSS water level monitoring systems

4.2 Recommendations

In terms of hardware, higher battery capacity installed at the rover station is recommended to account for rainy and cloudy days. Researchers can also look into more stable energy sources to continuously power the system.

Instead of a water level staff, data validation using depth gauges can also be explored to derive a second-to-second comparison with the RTK and PPK solutions. However, it should be noted that the water level measurements of depth gauges may be affected by land displacement movements.

While it was established that RTK solutions are generally derived from GPS and GLONASS constellations, it is recommended to configure the system to utilize other data correction format such as Compact Measurement Record (CMR) to include other satellite systems. Researchers may also look into different configurations of mask angle as well as changing the reference height of the water level measurement (e.g. from 0-m to 5-cm) to derive its effect in the solutions.

Lastly, this study shows promise of potential applications in other fields involving the use of real-time positioning in water monitoring purposes other than the water level parameter. Some of the fields include modeling ocean total alkalinity improvement that is free from the effects of spatial variability by incorporating widened scope of variables from various marine locations and employing the low-cost GNSS system for real-time geotagging. Additionally, localized CORS composed of LC static receivers that can provide cm-level accurate corrections can also be an application of the study.

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