Can GNSS Derived Height Replace Levelling Height? - A Case of Low-Land of Nepal

Shankar K.C.[1], Stallin Bhandari [1], Sandesh Upadhyaya [1], Sanjeevan Shrestha [1]
shankarkc01@gmail.com, stallin.bhandari@gmail.com, sandeshupadhya1@gmail.com, shr.sanjeevan@gmail.com
[1]Survey Department

KEYWORDS

GNSS derived orthometric height, GNSS, geoid, precise levelling, ellipsoidal height

ABSTRACT

Orthometric height is the generally adopted type of height worldwide and in geomatics community. Precise levelling has been the method of obtaining orthometric height in past for most of the country, so as the Nepal. However, due to wide usage of Global Navigation Satellite System (GNSS), the alternative approach of combining GNSS derived ellipsoidal height with geoid undulation to get GNSS derived orthometric height, has been used extensively. In Nepal, this technique was officially adopted in 2020 for Everest height measurement and understood as the efficient way to comply with levelling height. In this study, GNSS surveying was conducted on 15 stations located at the lowland region of Nepal and orthometric heights were obtained from GNSS and geoid method. When compared GNSS derived orthometric height with precise levelling height, the difference remained within threshold of 5cm for majority of observation stations. However, these differences are not sufficient to support the standards set for the third order levelling by Survey Department (SD). The accuracy of GNSS derived orthometric height can be significantly affected by various environment and existing resources such as existing accuracy of geoid, nature of precise levelling height. Considering the revisit upon these conditions, we expect GNSS-levelling as a strong alternative to time consuming, tedious, and costly precise levelling which is most suitable method of obtaining orthometric height in lowland topography at a precision less than 4 cm.

1 INTRODUCTION

1.1 Background

The global navigation satellite system (GNSS) is one of the most popular surveying techniques for determining 3D-position of various objects. This includes establishment of control points for detailed surveying as well as mapping purposes. Despite the fact that GNSS produces accurate 3D position on the earth, its height refers to the ellipsoidal height and does not refer to the vertical datum. The mean sea level (MSL) is the most common local vertical datum and spirit levelling has been employed continually to provide orthometric heights that always coincide with the local vertical datum. Although constructing a vertical datum for practically every country require substantial effort and financial investment, levelling procedures are employed to determine height. It is now feasible to obtain orthometric height using the GNSS technology, also known as GNSS-derived height, thanks to the development of accurate local geoid

(Menegbo, 2017). In many countries, like the United States of America, Australia, Japan, Korea, etc., it has been widely employed as a replacement for spirit levelling since it is more time and cost efficient (Lee et al., 2021).

Through Geodetic Survey Division (GSD), the Survey Department (SD) of Nepal is constantly striving to construct a geodetic network by carrying out several activities across the nation, including precise levelling, astronomical survey, gravity survey, GNSS and other geodetic survey work activities. Focusing on the vertical reference system, vertical datum of Nepal has been realized from extensive network of levelling networks of around 7600 km along the major roads at a period of around half century. Owing to the issues of existing vertical reference system which is passive by nature, continuously deformed as a result of seismic deformation and secular and annular shifts, in-sufficient levelling network due to time and cost intensive in nature etc.- SD is aiming to develop hybrid geoid model for vertical datum. As a starting point, SD has prepared a locally constrained nationwide geoid and used a GNSS-derived height determination approach to determine the height of Mount Everest. The establishment of a permanent bench mark (PBM) and its orthometric height using GNSS observation is one of the potential uses of the hybrid geoid model in the future. To do this, it is necessary to guarantee the GNSS based height's precision and efficiency in comparison with the levelling-based height. Although levelling work has been replaced by GNSS based height in many countries (Featherstone, 2008; Even-Tzur & Steinberg, 2009; Ampatzidis *et. al,* 2018; Oluyori *et. al,* 2018; Sikder et. al, 2020), there has been no research on this topic in Nepal. Conseqeuntly, in order to examine the prospect of replacing levelling height with GNSS-derived height, the study evaluates the precision of the GNSS derived orthometric height in low-land of Nepal by comparing it with levelling based height.

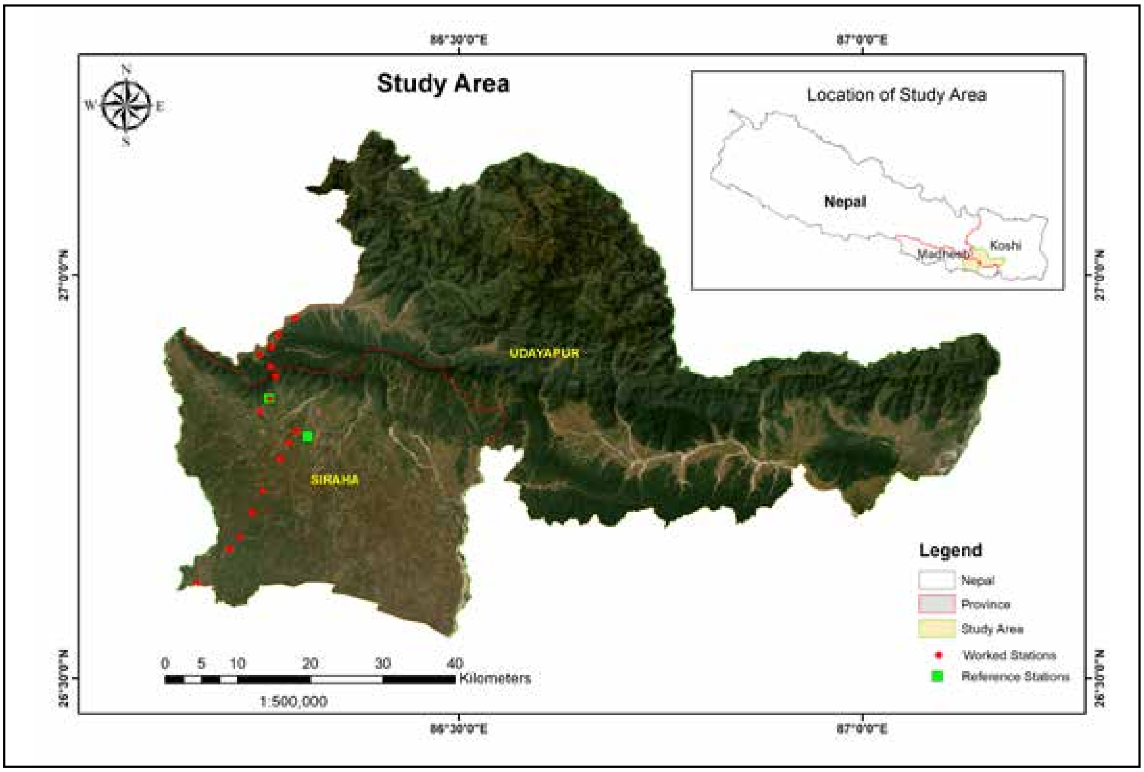

Figure 1 : Study Area

1.2. Study Area

The study area is located at the lowland region of the Terai, Nepal. In this study, 15 permanent levelling benchmarks (PBM) were surveyed and used. The lowland belongs to Siraha district and Udayapur district. The spatial extent of study area is: 26° 37' 7.6368" N to 26° 56' 46.9464" N in latitude and 86° 10' 30.4752" E to 86° 18' 44.5824" E in longitude. The elevation range of selected PBMs in the study area is around 180m (178.19m), with lowest and highest PBMs at an elevation of 8.65m and 186.84m respectively.

These PBMs are located along Chorhawa Siraha Madar Road, East-West Highway, and Mirchaiya-Katari Road. Since a refined geoid of this region was developed during Sagarmatha Height Measurement project, this site was chosen for the study purpose.

2. Methodology

Table 1: Survey Strategy for GNSS-derived height determination in Lowland of Nepal

Parameter	Specification
Observation period per session	4 hours
Number of sessions	2
Data logging interval	15s
Survey type	Static, Differential
Receiver	Multiple frequency
Check for the consistency of baseline processing results	Smaller than 3 cm between 4 h solutions of the first and second session
Geoid model	Geoid model prepared during Sagarmatha Height Measurement Project

2.1. Data Acquisition Strategy

For determination of GNSS-derived height, two stations were run daily as reference stations, namely: base 1 & base 2, while in PBMs, GNSS survey was carried out in differential GNSS mode. Therefore, base 1 and base 2 serve as master stations, while other PBMs were used as rover stations. Every PBM was surveyed twice with two sessions of 4 hours period separated by a time interval taken to shuffle the receivers and restart the survey. For example, 3 BMs were occupied by 3 GNSS receivers for the first 4 hours of a day and then GNSS receivers were shuffled between those same 3 BMs and occupied for the next 4 hours. The intention of the second occupation at the same station was to make separate observations in different scenario, so that, the geometry of satellite and the receiver changes at different session. These different scenario provides the redundant observations. In addition to redundancy, occupying the same stations twice offers independent check of the recorded observations. The general specification of surveying strategy is shown in Table 1.

2.2 Data Processing Strategy

Following the observation, GNSS data processing was carried out using the RTKLIB (*RTKLIB: An Open Source Program Package for GNSS Positioning*, n.d.) and Trimble Business Center (TBC) software. The detailed explanation are discussed in following sections.

2.2.1 Data Preparation/Data Cleaning:

This stage involved downloading data from the GNSS receivers; conversion to Receiver Independent Exchange (RINEX) format, and checking and making corrections to station metadata, such as proper naming, instrument height etc. as needed.

2.2.2 Precise Point Positioning (PPP) of Reference Stations:

Two reference stations' positions were determined using the PPP (Teunissen & Kleusberg, 1998) approach. The PPP technique was implemented using RTKLIB. The location of a station was calculated in standalone and absolute mode in PPP approach. Processing was done on the dual frequency signal's pseudorange and carrier phase data. Errors are meticulously fixed using IGS precise satellite orbit and clock products. Both receiver phase center offset (PCO) and phase center variation (PCV) for the relevant antenna model were used during processing. Ionosphere error was removed by Ionosphere-Free combination method while troposphere error was corrected using standard model and residual troposphere error was estimated along with carrier phase ambiguity, coordinate and receiver clock. The error in position due to earth and ocean tide was corrected using tidal loading models.

2.2.3 DGNSS Positioning of PBMs:

The position of each PBMs were computed relative to the reference stations based on the Differential GNSS positioning method (*Differencing | GEOG 862:*, n.d.) in TBC platform. DGNSS is applied in a short baseline scenario where double differencing is used to eliminate errors from the satellite and atmosphere, such as satellite orbit error, satellite clock error, relativity error, ionosphere error, and troposphere error. This is due to the fact that both satellite and atmospheric errors remain common at two end of the short baseline. Based on this differential positioning technique, the absolute positions of PBMs were derived relative to the base stations.

The final coordinates of PBMs were calculated after performing network adjustment with fixed coordinates of reference stations. These final adjusted coordinates in the form of triplets (Latitude, Longitude and ellipsoidal height) were used for further analysis.

The GNSS observations were collected and processed over the course of two different sessions to properly detect and correct blunders. Since the study aims to work on vertical component of the result, the study focused on the uncertainty of the ellipsoidal height. The difference between the vertical precision obtained from first session was compared to second session and the baselines with difference falling within 3cm (Lee *et al.,* 2021) were accepted for further processing.

2.2.4 Precise Levelling Height:

The precise levelling heights of individual PBMs along the alignments under the study were obtained from the Levelling and Gravity Section, GSD, of SD, Nepal. These precise levelling heights were compared against the GNSS-derived orthometric height calculated from GNSS and geoid approach.

2.2.5 Extraction of Geoid Undulation

Geoid undulation values at the PBMs, required for deriving orthometric heights, were extracted from Nepal Geoid 2021 with an accuracy of around 8 cm within the study area (unpublished). The geoid was fitted to local MSL obtained from precise leveling heights. The orthometric heights were calculated from both fitted and non-fitted geoid. The geoid fitting job had a mean of 2.141 cm and a standard deviation of 4.1 cm.

2.2.6 Computation of Orthometric Height

Equation 1 was used to derive the orthometric height from the ellipsoidal height obtained from GNSS observations using geoid undulation values (Heiskanen & Moritz, 1967).

$$H = h - N \qquad (i)$$

Where, H is orthometric height, h is ellipsoidal height, and N is geoid undulation (fitted and non-fitted both).

2.2.7 Comparison of Precise Levelling Heights & Orthometric Heights

The comparison of GNSS derived orthometric height and precise levelling height were performed in two ways. Firstly, the orthometric height and precise levelling height at each benchmark was compared by computing difference and the nature of such difference was examined. Secondly, the consecutive difference in GNSS derived orthometric height and in precise levelling height between consecutive pair of PBMs were computed and compared against third order levelling tolerance prescribed by GSD in levelling instruction book (Shrestha, 1988) as well as tolerance prescribed by ICSM guideline, Australia (Intergovernmental Committee on Surveying and Mapping, 2020). The formula for the tolerance set by GSD and ICSM for third order levelling can be derived from the equation (2) and (3) respectively.

Tolerance=$5.0\sqrt{k}$mm .... (*ii*)
(3rd order leveling)
Tolerance=$12.0\sqrt{k}$mm............................... (*iii*)
(3rd order leveling)

Where, *K* is length of levelling alignment in km.

3. Results:

3.1 Precision Analysis

In this section, the vertical precisions of baseline processing acquired in both sessions were compared to check the consistency. In this comparison, the baseline from base 2 to Madar had a significant variance, measuring 3.8 cm. The comparison for other baselines showed differences below 3cm. It suggested consistency in vertical accuracy for baseline processing of the observation. Thus, data of both sessions were merged and processed to get the final horizontal position and ellipsoidal height of PBMs.

Figure 2 shows the differences between GNSS derived orthometric height (from fitted geoid) and those obtained from precise levelling for the 15 unknown stations (BM's) located at the lowland of terai area. As shown in figure 2, 10 out of 15 stations (67%) observation showed difference smaller than 3 cm. The difference was smaller than 1, 2, 3 and 4 cm at five stations (33%), six stations (40%), 10 stations (67%) and 12 stations (80%). Only 20% (3 stations) of observation showed the difference in the range of 4-10 cm with maximum difference of 8.04cm at station 203-014.1.Thus, the mean absolute difference was calculated to be approximately 2.93cm.m

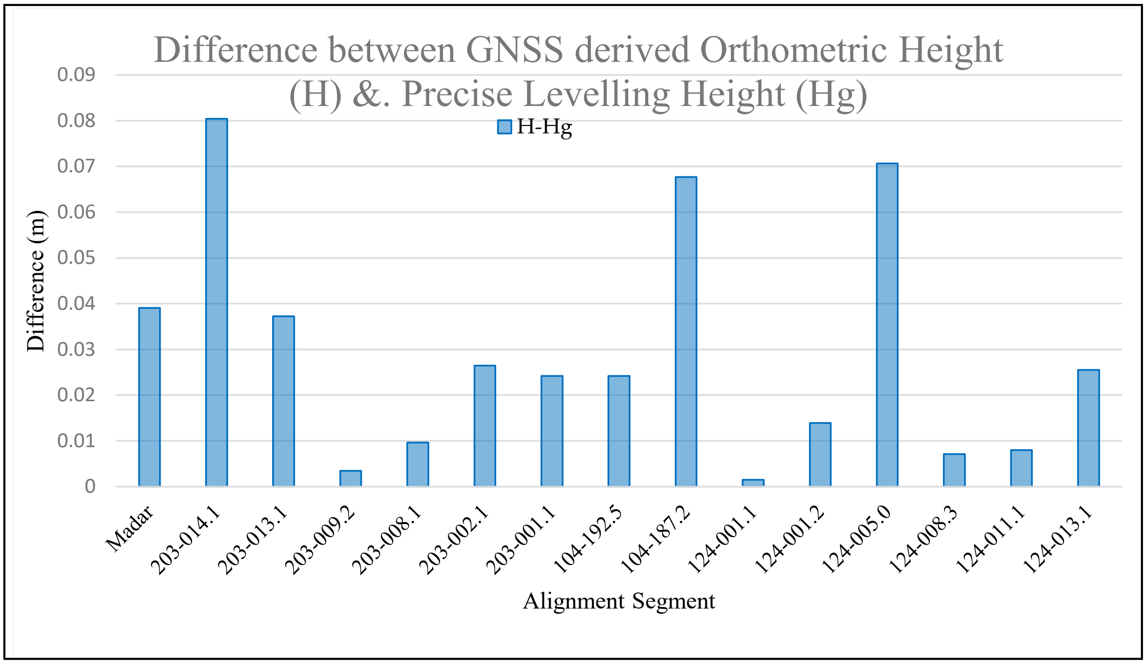

Figure 2: Plot of difference between GNSS derived orthometric height (from fitted geoid) and precise levelling height at each benchmark (Each bar corresponds to each BM and represent difference between orthometric height obtained from GNSS/geoid method and corresponding precise levelling height at that BM. The black horizontal line represents difference of 0.05m.)

3.2 Possibility of substituting GNSS derived orthometric height for third order levelling

Relative height differences between each successive station were calculated for both precise levelling heights and orthometric heights. This relative difference has been called consecutive height difference here. Difference of these two consecutive height differences was then compared with tolerance of third order levelling. The difference of relative difference of orthometric height and relative difference of precise levelling height (from both fitted and non-fitted geoid), the Tolerance of third order levelling set by GSD (equation (2)) and tolerance of third order levelling set by ICSM (equation (3)) are shown in Figure 3.

The result of relative differences from fitted geoid shows that only 6 segments (43%) fall within tolerance set by ICSM and only 4 segments (28%) fall within in tolerance set by GSD (see Figure 3). Whereas, The result from non- fitted geoid shows that only 6 segments (43%) segments fall within tolerance set by ICSM and only 4 segments (28%) fall within in tolerance set by GSD (see Figure 3).

The differences between GNSS derived orthometric heights from fitted geoid and precise leveling heights shows that only 7 segments (50%) fall within tolerance set by ICSM and only 4 segments (29%) fall within tolerance set by GSD. The remaining segments mostly deviate from the tolerance value.

The result refers that, based on present scenario, GNSS derived orthometric height cannot replace the third order levelling in lowland of Nepal. This may be due to the fact that GNSS derived orthometric height determination is largely affected by the site specific environmental conditions and available infrastructure for GNSS height derivation, the detailed explanation is placed in section 4..

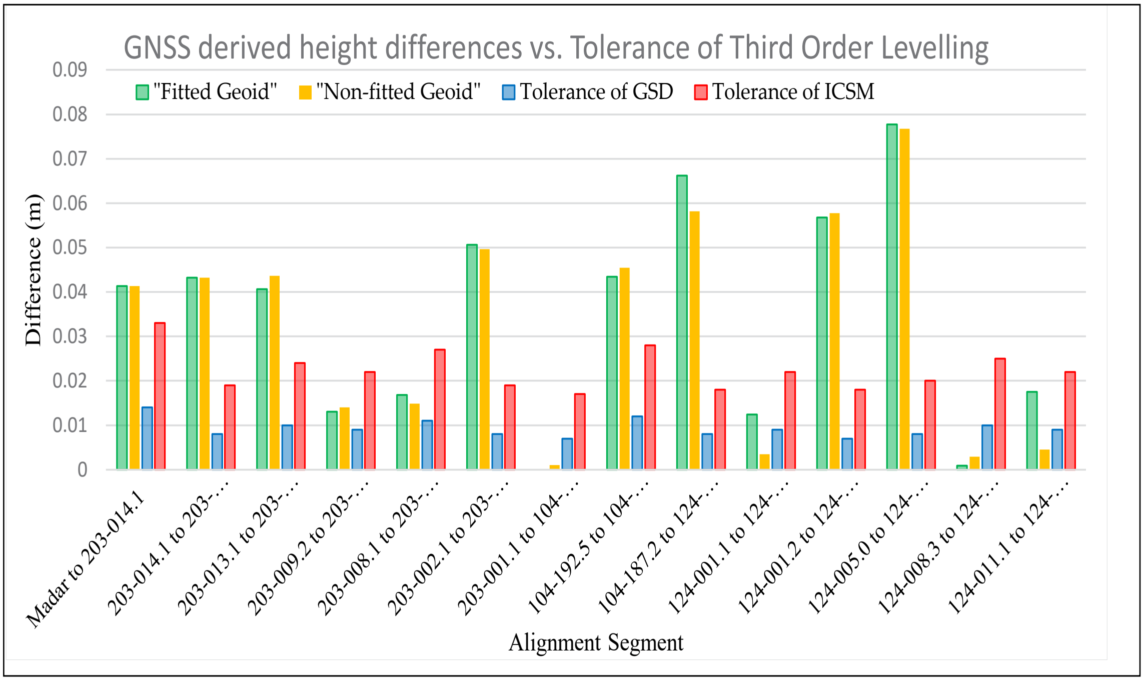

Figure 3: Plot of comparison of GNSS derived orthometric height differences (both from Fitted geoid and non-fitted geoid) with Tolerance of third order levelling, set by GSD and ICSM (At each segment, the difference of difference in orthometric height and difference in precise levelling height is computed and compared against tolerance of third order levelling according to GSD and ICSM.)

4. DISCUSSION

In this section the potential sources that could have deteriorated the precision of GNSS derived orthometric height has been discussed in detail.

4.1 Site Conditions and Multipath Effect

Referring to the Figure 1, only at 3 stations- 203-014.1, 104-187.2, and 124-005, the orthometric heights deviates from its precise levelling heights by more than 4cm. Examining the site condition of these stations, it was found that these stations were substantially effected by multipath conditions, as shown in figure 4. This is due to the fact that, the PBM stations are generally constructed to avoid unwanted intervention to keep PBMs safe. So, there are several cases where the PBMs are unfit for GNSS survey, resulting in significant multipath errors, which is the case in aforementioned stations.

At site (a), sorroundings have buildings and west of the station is covered by trees. Site (b) is the Mirchaiya Chowk park. Tall Ashok trees sorround the the boundary of the park, where the station is at the mid of the park. These sorrounding trees caused large mulitpath from every possible side. The site (c) is at the edge of road that pass through jungle. At these sites: 1) poor visibility of satellites, 2) poor satellite-receiver geometry and 3)multipath effect from every possible sides, caused the ellipsoidal height to be large error.

Figure 4: Site condition of PBMs whose ellipsoidal height has large errors

4.2 Precision of Existing Geoid

The precision of geoid has large role on the resulting accuracy from GNSS derived orthometric height. Reportedly, Korea has developed a geoid called KNGeoid18 having degree of fit of 2.3 cm and obtained the precision of around 3 cm in GNSS derived orthometric height determination approach (Lee et al., 2021). Similary, Australia has created its own geoid, known as the AUSGeoid, which is accurate to within 4-8 cm. Australian height datum (AHD) can be computed directly from the GNSS and AUSGeoid of accuracy of 6-13 cm (Intergovernmental Committee on Surveying and Mapping (ICSM), 2021) Additionally, Thailand's gravimetric geoid model 2017 (THAIG17) has rmse of 4.9 cm, which results in accurate heights of at least 10 cm accuracy level or better (Dumrongchai et al., 2021). However, the study used the geoid (geoid 2021) to extract the geoid undulation has reported accuracy of only about 8 cm in the sagarmatha region and 4 cm in the current study area. This demonstrates that the majorities of the countries that have employed geoid for GNSS-levelling work have prepared the geoid precise with greater precision than we have achieved so far. Therefore, we can conclude that the current geoid lacks the precision for GNSS-levelling works up to the precision of third order levelling.

4.3 Accuracy of Precise Levelling Height

In Nepal, the heights obtained from precise leveling height are actually geometric heights. Gravity correction must be applied to geometric height to derive pure orthometric height which is a physical height in a true sense. Therefore, the GNSS derived orthometric height cannot be easily compared with them given the nature of the precise levelling height that is currently available. Moreover, these heights are not network adjusted height either. The significant disparity in relative differences between them may have also been brought on by these conditions.

5. CONCLUSIONS

This study compared orthometric heights obtained from GNSS and geoid approach (both fitted and non-fitted) with precise levelling heights at 15 BMs which are located at lowland of Terai of Nepal. When GNSS-derived height, from fitted geoid, of 15 unknown points (BMs) were determined based on surveying for 4h/day for two different sessions, it is found that around 78% of points showed differences smaller than 4 cm as compared to the precise levelling results. Though the maximum difference was 8.04cm, the mean absolute difference remained within 2.93 cm. Those 3 stations which have difference larger than 4 cm were found to be situated at places with poor site conditions. If such site conditions are avoided and heavy multipath potentiality is avoided, the difference between orthometric height and precise levelling height can be restrained below 4cm in the lowlands of Nepal.

In addition, comparing the relative difference of GNSS derived orthometric height (from both fitted and non-fitted geoid) and relative difference between precise levelling heights between successive PBMs with tolerance of third order levelling prescribed by GSD and ICSM, it is found that, 28% (4/14 of leveling segments) falls within tolerance of GSD and 43% (6/14 of leveling segments) falls within tolerance of ICSM.

The result shows that GNSS derived orthometric height cannot replace the third order levelling in lowland of Nepal in present scenario as the accuracy of geoid in the study area was found to be around 4 cm only. Moreover, it should be noted that the tolerance set by other countries is higher than that set by GSD.

6. RECOMMENDATIONS

The study demonstrated that, unlike other countries, our current infrastructure supporting the vertical reference system prevents us from substituting GNSS derived orthometric height for precise levelling height of the third order. Therefore, the suggestions listed below are made to improve the situation so that GNSS derived orthometric height can be used instead of precise levelling height for third order levelling or lower.

- The current site conditions, on which levelling points are constructed, are usually unfavorable for GNSS observation leading to a large vertical position discrepancy. Therefore, it is recommended to establish the levelling points for the future with GNSS observation in mind.
- The available precise levelling height at present is geometric height without network adjustment. It is recommended that such geometric height be subjected to gravimetric correction to convert these into physical height. In addition, network adjustment should be applied to these heights. This makes the orthometric heights acquired using GNSS-geoid technique and the height achieved via precise levelling equivalent.
- The precision of the current geoid cannot be compared to the geoid prepared by the rest of the countries utilizing GNSS levelling as a substitute. Therefore, it is advised to increase geoid's precision in the future.
- When compared to the tolerance set for the same order of levelling by other countries, it can be seen that SD's tolerance for different order levelling is very low. Therefore, it is recommended to review the current levelling guidelines to align with global settings.
- This study used the reference collocated points at the low-land of Nepal, having height difference of nearly 180 m. The study's conclusion might not be precise given the wide diversity of heights in Nepal. Therefore, it is advised to continue the study using the contiguous points that cover every physiographic region of Nepal.
- Additional surface gravity surveys should also be conducted throughout the country to improve accuracy of gravimetric geoid as only certain protion of Nepal has been covered during Western Terai LiDAR Mapping Project and Everest Height Measurement Project. (Bhandari et al, 2022)

REFERENCES

Ampatzidis, D., Bitharis, S., Pikridas, C., & Demirtzoglou, N. (2018). On the improvement of the orthometric heights via GNSS-levelling:. *Geodäsie Geoinf. Landmanag.*, 235-241.

Bhandari S, KC S & Upadhyaya S (2022). *Gravimetry in Survey Department: A brief history and current practices.* Journal of Land Management and Geomatics Education, 34-38.

Differencing | GEOG 862: GPS and GNSS for Geospatial Professionals. (n.d.). Retrieved April 23, 2023, from https://www.e-education.psu.edu/geog862/node/1727

Dumrongchai, P., Srimanee, C., Duangdee, N., & Bairaksa, J. (2021). The determination of Thailand Geoid Model 2017 (TGM2017) from airborne and terrestrial gravimetry. *Terrestrial, Atmospheric and Oceanic Sciences*, *32*(5.2). https://doi.org/10.3319/TAO.2021.08.23.01

Even-Tzur, G., & Steinberg, G. (2009). Using an official undulation model for orthometric height acquisition by GNSS. *Survey Review*, 292-300.

Featherstone, W. (2008). GNSS-based heighting in Australia: Current, emerging and future issues. *Journal of Spatial Science*, 115-133.

Heiskanen, W. A., & Moritz, H. (1967). *Physical Geodesy* (3rd ed.). W.H. Freeman and Company.

ICSM, (2020). *Guideline for Control Surveys by Differential Levelling v2.2.* Intergovernmental Committee on Surveying and Mapping. https://www.icsm.gov.au/sites/default/files/2020-12/Guideline-for-Control-Surveys-by-Differential-Levelling_v2.2.pdf

ICSM, (2021). *Australian Vertical Working Surface (AVWS)*. Intergovernmental Committee on Surveying and Mapping (ICSM), Geodesy Working Group (GWG).

Lee, J., Kwon, J. H., & Lee, Y. (2021). Analyzing Precision and Efficiency of Global Navigation Satellite System-Derived Height Determination for Coastal and Island Areas. *Applied Sciences*, *11*(11), 5310. https://doi.org/10.3390/app11115310

Menegbo, E. (2017). Determination of orthometric elevations using gnss-derived height with the egm2008 geoid height model. *International Journal of Advanced Geosciences*, *5*(1), 13. https://doi.org/10.14419/ijag.v5i1.7190

Oluyori, P., Ono, M., & Eteje, S. (2018). Computations of Geoid Undulation from Comparison of GNSS/Levelling with EGM 2008. *International Journal of Scientific and Research Publications*, 235-241

RTKLIB: An Open Source Program Package for GNSS Positioning. (n.d.). Retrieved April 23, 2023, from https://rtklib.com/

Shrestha, N. N. (1988). *Levelling Instruction Book*. Survey Department, Geodetic Survey Branch.

Sikder, M., Wu, F., Ahmed, W., Thodsan, T., & Zhao, Y. (2020). Assessment of Orthometric Height Derived from Levelling, GNSS. In Proceedings of the 2020 15th IEEE International Conference on Signal Processing, (pp. 689-694). Beijing, China

Teunissen, P. J. G., & Kleusberg, A. (Eds.). (1998). *GPS for Geodesy*. Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-72011-6

Author's Information

Name	:	Shanker KC
Academic Qualification	:	BE in Geomatics
Organization	:	Geodetic Survey Division, Survey Department
Current Designation	:	Survey Officer
Work Experience	:	5 years
Published paper/article	:	4