# Generation of Geological Database for Liquefaction Hazard Analysis in Kathmandu Valley, Nepal

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ABSTRACT
The fluvio-lacustrine deposit of Kathmandu basin has been studied using 185-borehole logs information ranging in depth from 35 meter to 575 m. The entire basin fills in this study is divided into three distinct layers as Bottom of Lake deposit, Lake deposit and top of Lake deposit and layer models for each are generated using ILWIS 3.2 version. The layer models also led to generate thickness map of each layer. The layer models were compared with the lithological cross section drawn along the same direction and it was correlated. Next, a liquefaction susceptibility map for Kathmandu Valley has been produced using 328 shallow boreholes with depth less than 30 m. Both qualitative and quantitative methods were applied for the analysis and were compared. Finally a liquefaction susceptibility map of Kathmandu valley has been prepared.

## 1. INTRODUCTION

Kathmandu valley lies in a very active seismic zone. Several big earthquakes have hit the city in the past. There have been numerous devastating earthquakes within living memory such as in 1934, and 1988 (Table 1). There were also significant historical earthquakes recorded in 1833 and in 1255. Due to lack of instruments and technical know how, these earthquakes were not recorded instrumentally in Nepal. According to reports (Rana 1935), huge damage and casualties had occurred due to these events. Normally there are frequent small to medium size earthquakes occurring in different parts of the country with localized effect. Nepal is becoming increasingly vulnerable to earthquakes with each passing year. This is due to the increasing population, uncontrolled urban development, and a construction practice that has actually deteriorated over the last century.

Looking at the urbanization of Kathmandu valley now, if a similar earthquake as that of 1934 was to occur today, the scenario would be devastating, and the fatalities would be very high. For that earthquake scenario, the Japan International Cooperation Agency (JICA, 2002) estimated up to 59,000 houses destroyed, 20,000 deaths and 59,000 seriously injured. Another study carried out in the framework of the Kathmandu Valley Earthquake Risk Management Project (Dixit et.al., 1999) estimate a total of 40,000 deaths, 95,000 injuries and 600,000 or more homeless for the same scenario earthquake. This situation has created the necessity for carrying out a detailed seismic hazard assessment of the city and an awareness building measures to the people of Kathmandu valley regarding the earthquake safety. It is also important to carryout more earthquake vulnerability reduction programs in Kathmandu valley.

For such an earthquake vulnerability program, data concerning the subsurface geology as well as geological structures is very important. Knowledge on such features plays a key role in the generation of damaging phenomena during an earthquake. A good knowledge of the subsurface soil conditions is very important for the assessment of local site response for sensitivity analysis, building vulnerability analysis, road and infrastructures vulnerability analysis etc. As Kathmandu valley is extremely vulnerable to damaging earthquakes, it is highly important that the local authorities take their responsibility in the vulnerability reduction process so that the future loss of lives and damage can be minimized.

Liquefaction is one of the main effects of an earthquake that is responsible to structural failure and damage to roads, pipelines and infrastructures. In Kathmandu valley in spite of weak subsurface condition, many tall buildings have been built and the number is constantly rising. Most of these buildings have been constructed without adequate research on the subsurface sediment conditions and hence may run a high risk that they are not properly designed to withstand the particular accelerations at the site. Looking at this situation, the study on subsurface geology is very important. Reports from previous major earthquakes, such as the one from 1934, give evidence that substantial damage to buildings and infrastructures can occur in Kathmandu valley as a result of widespread liquefaction. Therefore, it demands for the detailed mapping of liquefaction hazard assessment in Kathmandu valley. To carry out a reliable liquefaction hazard assessment, borehole data with geotechnical information are important. On the other hand, a complete inventory of borehole data with geotechnical information for Kathmandu valley is missing.

To date, the actual number of drill holes made in Kathmandu Valley is not known. It is believed that more than 300 deep drill holes have been made in the area by different organizations. Yet not a single organization has made an attempt to manage the complete borehole log information. The borehole information is limited in the hands of concerned organization that carried out the drilling project. As such, accessibility of such data to the professionals who are interested to carry out research work is limited. This is why it is required to collect all those primary data from the source organizations and organize it in a proper data base system including a geographical component related to the location of the boreholes.

## 2. GEOLOGICAL SETTING OF THE STUDY AREA

The Kathmandu valley is situated between latitude $27^0$ 32'N to $27^0$ 49'16" N and longitude $85^0$13'28" E to $85^0$ 31'53" E (Figure 1). The Kathmandu valley is an intermontane basin and is filled by thick lacustrine and fluvial sediments from Pliocene to Quaternary in age (Yoshida and Gautam 1988). It is surrounded by high rising mountain ranges, such as Shivapuri (2732 m) in the North and Phulchauki (2762 m) in the South (see Figure 1). The Kathmandu valley comprises of quaternary sediments on top of basement rocks. According to Stöcklin and Bhattarai (1977). The basement rock of Kathmandu Valley consists of Phulchauki group and Bhimphedi group of the Kathmandu complex and is formed by Precambrian to Devonian rocks. The rocks of Kathmandu complex along with the underlying para-autochthonous Nawakot Complex constitute the Mahabharat Synclinorium (Sakai 2001). The axis of this synclinorium passes along the Phulchauki-Chandragiri range, south of the Kathmandu Valley within the Kathmandu valley, the basement rocks are intersected by numerous fault systems. Some isolated rock outcrops of Tistung Formation and Chandragiri Formation can also be observed in some parts of the valley basin such as in Balkhu, Pashupatinath, Swayambhu and Chobhar. The Bhimphedi group of the Kathmandu complex mainly lies outside the watershed boundary of the Kathmandu valley; therefore, the source rocks of the basin fill sediments are limited to the Phulchauki group and Shivapuri injection complex. The geology of the Kathmandu basin can be divided into mainly three groups as southern, central and northern (Sakai 2001).The geology of the southern and central part is further subdivided into different formation types as given by Sakai (2001) in Table 2 and are correlated. The oldest formation, Bagmati Formation (central part) and Tarebhir Formation (southern part) (Sakai 2001), is unconformably overlying the Pre-Cambrian Tistung Formation. The formation is mainly composed of boulders and cobbles with minor amount of lenticular sand beds, which were fluvial in origin and were derived from the ancient river system. The age of this formation is believed to be from late Pliocene to early Pleistocene (Yoshida and Igarashi, 1984). On the other hand, the Kalimati Formation (central part) and Lukundol Formation in the southern part consists predominantly of dark gray carbonacious and diatomaceous beds of open lacustrine facies (Sakai, 2001), Diatomaceous beds were predominantly accumulated in marginal parts of the Lake and some landslide dammed ponds (Dill et al., 2001). This type of sediment is extensively distributed beneath the central portion of the Kathmandu valley. The thickness of this formation is very thick in the central part (304 m in borehole B1 at Harisidhi) and in the southern part it is thin. The age of this formation ranges from 2.5 million years BP to 29,000 BP (Yoshida and Igarashi 1984). Similarly the youngest formation, the Patan Formation (in the central part) and Itaiti Formation in the South comprises alternating sequence of gravel, fine sand and silty clay with carbonacious mud in ascending order. The Patan Formation is distributed extensively over Kathmandu and Patan cities and Itaiti Formation is distributed in and around Itaiti village in the Southern part of the Valley.

In the northern part of the valley the sediment comprises of terrace-forming sands from fluvio-deltaic or fluvio-lacustrine origins and are given names as Thimi Formation and Gokarna Formation (Yoshida and Igarashi 1984; Sakai 2001). Gokarna Formation is considered older than the Thimi Formation. The sediment of these formations is extensively distributed in the northern and northeastern part of the Kathmandu valley. The age of this group is considered between 29,000 BP to 23,000 BP (Yoshida and Igarashi, 1984).

## 3. GENERATION OF GEOLOGICAL DATABASE

Geological database using Microsoft Access has been set up for the storage of borehole data Figure 2. For the deep boreholes, three tables were generated and for the shallow one four tables were generated. So far, information of 185 deep boreholes with depth ranging from 35 m to 575 m has been collected for this study purpose. Out of these 185 boreholes, 23 are relatively shallow with drilling depths less than 100 m and the rest are greater than 100 m with maximum depth reaching up to 577 m located in the central part of the valley. Thirty six (36) of them have even reached up to the bedrock. The data collected so far for these boreholes contained information such as lithology, depth range, altitudes and static water table. The information of these boreholes was used for the generation of Layer models and lithological cross sections.

On the other hand, for the liquefaction hazard analysis 328 shallow boreholes with depth range less than 30 m were collected. The depth of these borehole ranges from a few meters up to 30 m. The borehole records contain both lithological and geotechnical information such as grain size distribution, Atterberg limits, N-values, moisture content, specific gravity, density, unit weight, angle of friction ($\phi$), direct shear and soil type. However, it is to be noted here that only a small number of boreholes included all these types of information.

The data so organized in Access were transferred to ILWIS tables and to the Rockwork99 tables for further analyzing and processing. ILWIS3.2 version was used for the generation of Layer models and Rockworks99/2002 was used for the generation of lithological cross sections and fence diagrams.

## 4. GENERATION OF LAYER MODELS

The availability of Sufficient and reliable borehole data enables to generate sub surface layer models, which is an important input for the assessment of local site response for sensitivity analysis building vulnerability analysis, road and infrastructures vulnerability analysis etc.

The main aim of the GIS layer modelling was to determine the thickness of the various subsurface deposits. The sediment distribution within the Kathmandu valley is very complex. The valley fill sediments which were mainly formed by fluvial and lacustrine activity are distributed heterogeneously both in depth and in space. In order to generate layer models for such a heterogeneous environment, a certain degree of generalization had to be accepted. In this case, the entire sediments of the basin are divided into three layers as Pre-lake deposit, Lake deposit and Post lake deposit demarcated by fixed altitude value (Figure 3). The layer-modelling concept is used in this study in order to separate between the lake deposits and the non-lake deposit so that the thickness of the different layers of the sediments could be determined and hence could be applied for the estimation of ground amplification during an earthquake.

For the generation of the bedrock altitude map, some assumptions were made to determine depth to bedrock for some wells as only 36 of the wells have actually reached up to bedrock level and the rest of the wells are ending still in the soft sediments. The development of a layer model for the depth to the bedrock using only 36 boreholes did not give good results. The problem was encountered during the construction of cross sections as evidenced by frequent intersection of layers. Hence for the rest of the wells the depth to bedrock level was based on the depth of the neighboring wells that have touched the bedrock level and also on the existence of rock exposure near by well locations.

During the processing and analysis of the data in ILWIS 3.2, an interpolation technique was followed in order to obtain the required GIS layer models. For the interpolation of soil depths, one of the most important input data consists of the locations where the soil depth is zero, and hard rock is exposed.

The area of the unconsolidated sediments was masked out from the catchment map of the study area in order to separate it from hard rock area. The boundaries of the unconsolidated sediments were used as points with a soil thickness of zero value and were combined with the depth information from the boreholes.

This was done because the number of boreholes was rather limited, and interpolation of these would result in large errors on the side of the valley, where there is no soil cover. Therefore, the segment boundary of the quaternary cover in the map was converted into points, and the elevation value obtained from the DEM was assigned to them. These points were then glued with borehole point map. The glued point map was then interpolated following the Simple Kriging method. Before the Kriging operation was performed, the spatial correlation operation was used for obtaining suitable (best-fit) semi-variogram models with omni-directional option and lag spacing of 500 m. In the output table obtained from the spatial correlation method semi-variogram models were plotted in a graph between Avg-lag versus semi variogram to make the best fit.

The best-fitted model (spherical) was chosen for the Kriging purpose as shown in Figure 4. Using the same procedure, four models were prepared for the different boundaries of the sediment layers.

The Kriging operation was carried out for four different levels: bedrock level, top of the lake deposit and bottom of the lake deposit and the surface. Thus, four Digital Elevation Models were representing these different layers as shown in Figure 5 (A, B, C, D) respectively. Similarly, the thickness maps of individual layers were derived by subtracting the various DEMs. Thus, three thickness maps were generated for the Post-Lake deposits, Lake deposit and Pre-Lake deposits as shown in Figure 6 (A, B, C). After the generation of the layer models, cross section was generated for different layers, following ILWIS procedures. The profile direction of the cross section is shown in Figure 6 D. Lithological cross section was also drawn using Rockworks99 along the same direction. An example of a cross section generated by ILWIS and the corresponding cross section generated through Rockworks is shown in Figure 7 A and B. The cross section generated in ILWIS runs from Bungmati in the Southern part to Budhanilkantha in the Northern part (see Figure 1 for location of the place). The figure indicates that, the sediments above the lake deposits gradually increase to the North, in the central part, this portion is less and in some part, it vanishes as well. On the other hand, the thickness of the lake deposits gradually diminishes to the northern part and to the extreme South but increases in the central part and to the South. Similarly, the sediments below the lake deposit can be observed more in the central and southern part except in Lalitpur and Pashupati area where bedrock is encountered at lower depths and hence the thickness appears less (see Figure 1 for location). This cross section is compared with the lithological cross section drawn almost along the same direction (see Figure 7 B). It shows that they are rather well correlated. For example in Figure 7 A, we can observe that the thickness of the lake deposit is more in the central part which is also represented by the boreholes WHO8, BHD3 and DMG8 respectively (see Figure 7 B). Similarly, if we go towards the northern part the thickness of the lake deposits gradually decreases, which is also represented by the boreholes BB2 and OW7 in Figure 7 B.

The borehole BB2 indicates the marginal line for the ancient lake territory. After that place further to the North, boreholes consist of abundance of coarse sediments. The sediment distribution of Kathmandu valley was also studied by generating Fence diagrams and stratigraphic projections using Rockworks99/2002 (Fig. 8, 9 and 10). The stratigraphic projection of the sediments in both the direction shows undulating behavior of the sediment contacts (see Figure 9 and 10). We can conclude, on the basis of the undulating contacts that the sediment depositions within the valley have been controlled by the irregular bedrock topography, for which the existing fault systems within and around the valley may have played a major role.

## 5. LIQUEFACTION HAZARD ASSESSMENT:

There are several methods developed for evaluating liquefaction potential areas. Generally, there are two methods Qualitative analysis and Quantitative analysis. In this study for the liquefaction susceptibility analysis both the methods are incorporated.

5.1. Qualitative analysis

In the qualitative analysis the method of Iwasaki et. al (1982) and Juang, and Elton method (1991) were adopted. The method of Iwasaki (1982) is based on topographical and geological information. According to it, terraces, hills and mountains are considered as non-liquefiable areas and riverbeds, flood plains and swamps are considered as liquefiable potential areas. According to this principle, at first the areas were delineated using stereo pair. On the other hand, liquefaction potential of each borehole was analyzed using the method of Juang and Elton (1991) method, which is based on scoring system. Out of the 12 factors considered by Juang and Elton, six of the factors were chosen for the analysis. They are Depth to water table, Grain size distribution, Burial depth, Capping layers, Age of deposition and Liquefiable layer thickness. These factors are considered to be very important for causing liquefaction at a particular place. All six factors were given appropriate score values depending on their influence to accelerate liquefaction in an area. Factors considered to be more influential were given greater weights. The sums were added and the final score obtained by summation of all the factors is considered to give a better indication of the soils susceptibility to liquefaction. Based on the final score obtained by summation of all the factors, four levels of liquefaction susceptibility have been selected as, High, Moderate, Low and Very Low (See Figure 11). The liquefaction level class assigned to different boreholes was compared with the average SPT values obtained for 10 m depth. A close agreement was found in most of the cases (boreholes), as most of the boreholes have SPT values less than 20. On the other hand some of the boreholes, which were designated as high or moderate liquefaction susceptible, have very high SPT values (greater than 30), which is rather exceptional. Hence these places where N- value are greater than 30 can be considered as non liquefiable areas though they obtained high scoring values with moderate or high class during qualitative analysis.

5.2. Quantitative analysis

In the quantitative analysis simplified methods developed by Iwasaki et. al (1984) and Seed and Idriss (1971) were adopted.

**Iwasaki - method**

A simple method suggested by Iwasaki et al. (1984) was used here to evaluate a liquefaction resistance factor, $F_L$. According to this method, liquefaction potential can be estimated simply by using the fundamental properties of soils, i.e. N-values, unit weights, mean particles of diameter and Peak Ground Acceleration of the ground surface (PGA). The liquefaction resistance factor was calculated using equation as given below.

$$F_L = \frac{R}{L} \qquad (1)$$

Where R is in situ resistance or undrained cyclic strength of the soil element to dynamic loads during earthquakes and can be evaluated using the equation as

$$R = 0.0882 * \sqrt{\frac{N}{\sigma'_v + 0.7}} + 0.225 Log_{10} \frac{0.35}{D_{50}} \qquad (2)$$

For $0.04 \le D_{50} \le 0.6mm$

$$R = 0.0882 * \sqrt{\frac{N}{\sigma'_v + 0.7}} - 0.05 \qquad (3)$$

For $0.6 \le D_{50} \le 1.5mm$

Where, N= Insitu SPT value, and $\sigma'_v$ is effective overburden pressure in kgf/cm$^2$ and $D_{50}$ is the mean particle diameter in mm.
Similarly,

$$L = \frac{\tau_{\max}}{\sigma'_v} = \frac{a_{\max}}{g} \times \frac{\sigma_v}{\sigma'_v} \times r_d \quad \ldots\ldots \quad (4)$$

Where $\tau_{\max}$ is the max shear stress in kgf/cm$^2$ $a_{\max}$ is the max acceleration at the ground surface in gals, g is the acceleration of gravity = 980 gals, $\sigma_v$ is the total overburden pressure in kgf/cm$^2$ and $r_d$ is the reduction factor of dynamic shear stress to account for the deformation of the ground. From a number of seismic response analysis for grounds, Iwasaki et al. (1984) proposed the following relation for the factor $r_{d,}$
$R_d$=1.0 – 0.015Z, Where Z is the depth in meters. --------------------------------------- (5)

According to this relation, the soil of the particular site is expected to be liquefied if the calculated Liquefaction resistance factor ($F_L$) becomes less than 1. The quantitative assessment following the Iwasaki method was carried out for 87 boreholes in 31 different sites. For Kathmandu valley Peak ground acceleration is considered as 0.1g according to the Indian earthquake standard IS 1093-1984 for earthquake zone V. It was found that out of the 87 boreholes, a total of 37 boreholes in 15 different sites showed a low liquefaction resistance factor at a particular depth and thus liquefaction is likely to occur during a strong earthquake. In the rest of the boreholes, liquefaction is not expected.

### 5.2.1. Seed and Idriss method

The quantitative analysis of liquefaction potential for a certain number of boreholes with geotechnical information was also performed using the standard method of seed and Idriss (1971). In this method, the potential maximum seismic shear stress in the ground is compared with the minimum cyclic shear stress causing liquefaction for a particular soil. The soil is susceptible to liquefaction if the maximum seismic shear stress in the ground is higher than the minimum cyclic shear stress causing liquefaction. Shear stress developed during earthquake ($\tau_{av}$) was computed using equation 6.

$$T_{av} = 0.65 \times \gamma h \times (\frac{a_{\max}}{g}) \times r_d \ldots\ldots 6$$

Similarly shear stress causing liquefaction was computed using the equation 7,

$$CSR = \frac{\tau_0}{\sigma'_0} = 0.65 \times \frac{a_{\max}}{g} \times \frac{\sigma_0}{\sigma'_0} \times r_d \ldots\ldots 7$$

For which the value for cyclic stress ratio (CSR) was obtained from the graph developed by Seed et al. (1975). A comparison was made between them and if $\tau_{av}$ was found greater than $\tau_0$, then the soil would be called liquefiable. The calculation was made for an earthquake of $M_s$ = 7.5, and PGA value of 0.1g. Following this method, the analysis was carried out for 69 boreholes located at 40 different sites. It was found that out of the 69 boreholes, in 35 of the boreholes liquefaction is likely to occur at a particular depth, and in the rest of the boreholes there will be no liquefaction for the estimated earthquake magnitude of 7.5 and PGA value of 0.1g.

The final liquefaction susceptibility map (Figure 12) prepared was compared with the qualitatively analyzed point map as shown in the Table 3. It was found that 65 of the boreholes classified as highly susceptible to liquefaction are correctly classified as high in classified map. Similarly 51 number of borehole samples are correctly classified as moderately susceptible in classified map. Like wise 11 numbers of boreholes are correctly classified as low and 2 of the boreholes are correctly classified as very low. Rests of boreholes are labeled in wrong zones.

## 6. DISCUSSION AND CONCLUSION

The study resulted in the generation of geological database and its use for generation of layer models and liquefaction susceptibility map. The database includes information for 185 deep boreholes as well as 328 shallow boreholes. The information for deep boreholes included lithology information, depth and water table. Whereas the information for shallow boreholes included lithology information, and geotechnical information. The database for deep boreholes led to the generation of three distinct layer models as post lake deposit, lake deposit and pre-lake deposit and to the generation of stratigraphic projections and fence diagrams. On the other hand, the database of shallow borehole led to the generation of liquefaction susceptibility map, categorized into High, Moderate, Low, and very low zones (Figure 12). Both qualitative and quantitative analyses were adopted in the analysis. One of the major drawbacks of both the qualitative and quantitative methods for liquefaction susceptibility mapping is the difficulty to translate the resulting classification into quantifiable terms that can be used for the actual loss estimation of buildings, infrastructure and population. Both methods indicate high, moderate or low susceptibility but do not indicate how much of percentage of the area is likely to experience liquefaction phenomena, and in with which intensity.

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Table 1: Earthquake magnitudes and epicenter distance of some famous historical earth quakes (JICA 2002).

| Date | Magnitude | Intensity | Latitude | Longitude | Epicenter dist. (Km) from Kathmandu | Assumed PGA (gal) |
|---|---|---|---|---|---|---|
| 1833 | 7 | | $28^0$ | $85^0$ | 38 | 137 |
| 1833/8/26 | 7 | X | $27^0$ | $85^0$ | 84 | 75 |
| 1833/10/4 | 7 | IX | $27^0$ | $85^0$ | 151(Kalaiya) | 47 |
| 1833/10/18 | 7 | VIII | $27^0$ | $84^0$ | India | NA |
| 1866/23/05 | 7 | X | $27.7^0$ | $85.3^0$ | Kathmandu | NA |
| 1869/7/7 | 7 | | $28^0$ | $85^0$ | 45 | 121 |
| 1934/1/15 | 8.4 | IX-X | $27.55^0$ | $87^0$ | 177 (North of Chainpur) | 188 |
| 1936/5/27 | 7 | NA | $28.50^0$ | $83.5^0$ | 199 | 38 |
| 1954/9/4 | 6.5 | NA | $28.30^0$ | $83.8^0$ | 163 | 34 |
| 1988/8/20 | 6.5 | | $26.75^0$ | $86.62^0$ | 167 (Udayapur) | 36 |

Table 2: Classification of sediments of the Kathmandu basin sediments by different workers

<table>
<tr><td colspan="3" rowspan="2">Yoshida & Igarashi (1984)<br>Yoshida & Gautam (1988)</td><td rowspan="2">Dongol<br>(1985, 1987)</td><td rowspan="2">Shrestha<br>et al. (1998)</td><td colspan="2" rowspan="2">Sakai et al. (2001)</td><td colspan="2">Sakai (2001)</td></tr>
<tr><td>Southern part</td><td>Central part</td></tr>
<tr><td colspan="3">Patan Formation</td><td rowspan="3">Kalimati Clays</td><td rowspan="14">Gokarna fm<br>Tokha fm<br>Kalimati fm<br>Chapagaon fm<br><br>Lukundol fm & Kobgaon fm</td><td rowspan="3"></td><td rowspan="3"></td><td rowspan="9">Itaiti Fm</td><td rowspan="9">Kalimati Fm</td></tr>
<tr><td colspan="3">Thimi Formation</td></tr>
<tr><td colspan="3">Gokarna Formation</td></tr>
<tr><td colspan="3">Boregaon terrace deposit</td><td rowspan="6">Champi-Itahari gravel</td><td rowspan="14">Lukundol Formation</td><td rowspan="6">Upper member</td></tr>
<tr><td colspan="3">Chapagaon terrace deposit</td></tr>
<tr><td colspan="3">Pyangaon terrace deposit</td></tr>
<tr><td rowspan="10">Lukundol Formation</td><td rowspan="10">Member</td><td>VIII</td></tr>
<tr><td>VII</td></tr>
<tr><td>VI</td></tr>
<tr><td>V</td><td rowspan="5">Nakhu Khola mudstone & Keshari nayakhandi lignite</td><td rowspan="5">Middle member</td><td rowspan="5">Lukundol fm</td><td rowspan="5">Basal lignite member</td></tr>
<tr><td>IV</td></tr>
<tr><td>III</td></tr>
<tr><td rowspan="3">II</td></tr>
<tr></tr>
<tr><td rowspan="3">Tarebhir basal gravel</td><td rowspan="3">Basal boulder bed</td><td rowspan="3">Lower member</td><td rowspan="3">Tarebhir Fm</td><td rowspan="3">Bagmati Fm</td></tr>
<tr><td>I</td></tr>
<tr><td></td><td></td><td></td></tr>
</table>

Table 3: Cross table between classified map and qualitatively analysed point map

| Sum of NPIX | LI-QUE_FACTI | | | | | |
|---|---|---|---|---|---|---|
| LIQUE_CLASS | High | Moderate | Low | Very Low | No | Grand Total |
| High | 65 | 27 | 2 | 0 | 0 | 94 |
| Moderate | 55 | 51 | 8 | 2 | 0 | 53 |
| Low | 16 | 22 | 11 | 3 | 1 | 116 |
| Very Low | 8 | 5 | 2 | 2 | 2 | 19 |
| Grand Total | 144 | 105 | 23 | 7 | 3 | 282 |
| | | | | | | |
| Overall accuracy = correctly classified pixels (sum of diagonal values)/total samples | | | | | | |
| Correctly classified pix-els | 129 | | | | | |
| Overall accuracy | 0.462366 | | | | | |

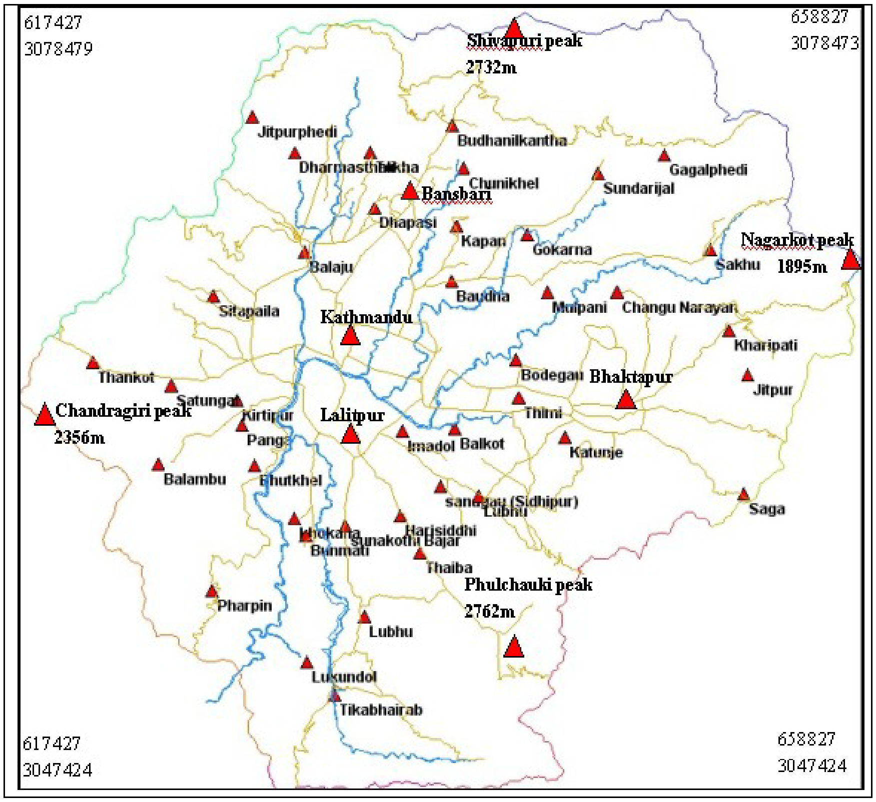


Fig. 1: Map of the study area.

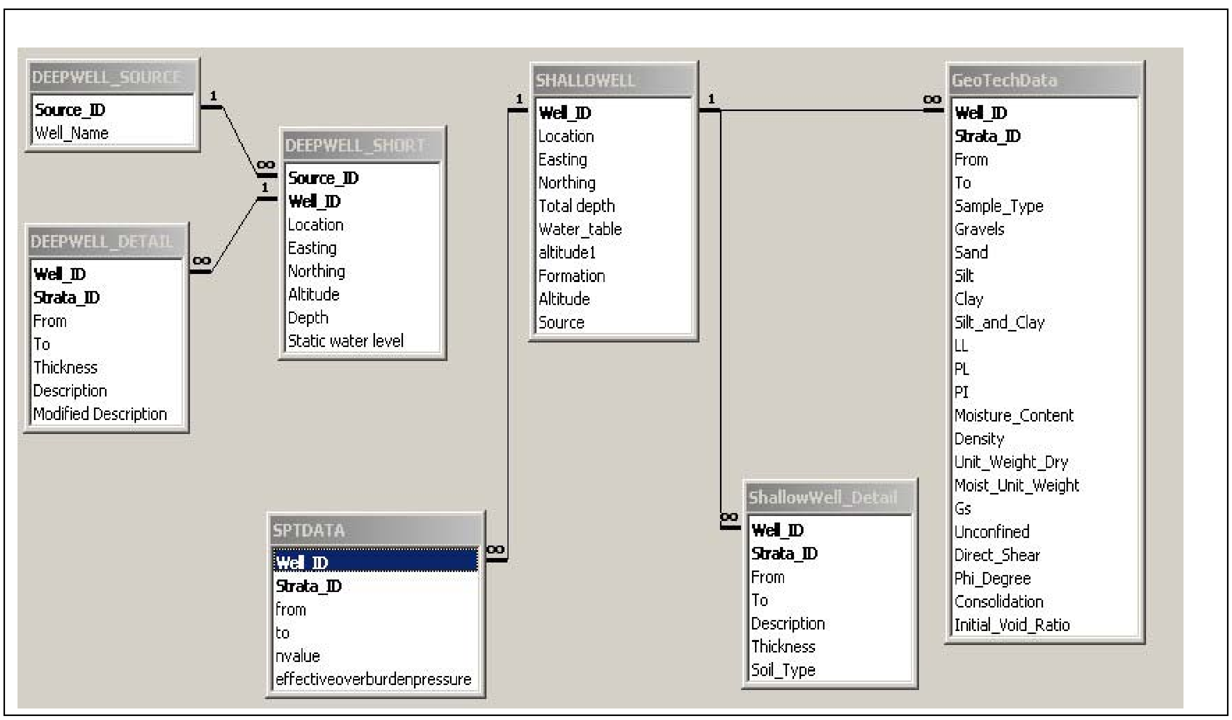


Fig.2: Relationship diagram of the borehole database

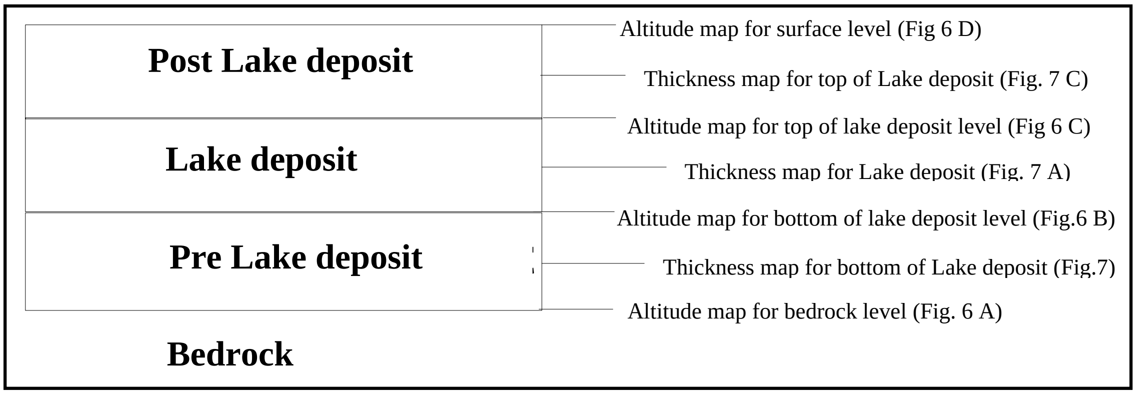


Fig. 3: Simplified profile of different layer of sediment deposits. The boundary of each layer is represented by respective altitude maps as given in the text and also the thickness maps of each layer are indicated.

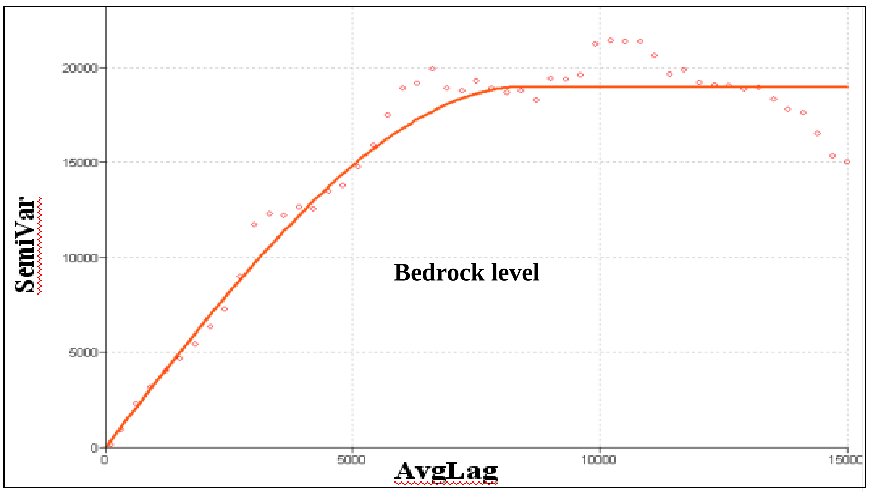


Fig. 4: Semi-variogram model for bedrock level

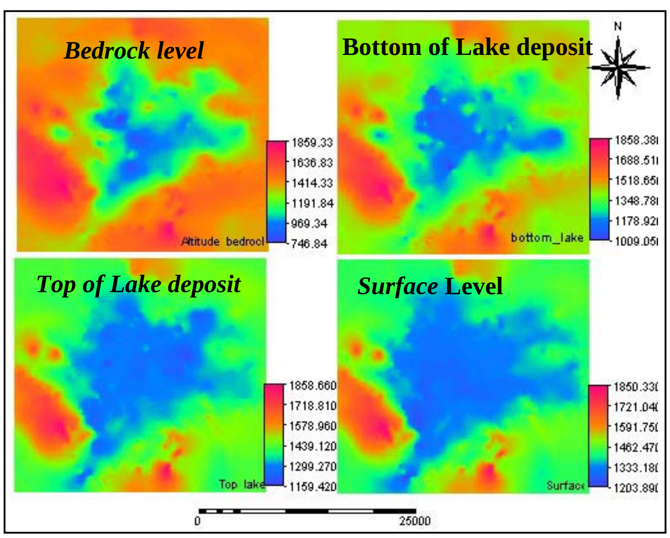


Fig. 5: Digital Elevation Models generated for the boundaries layers in the Four-layer model for Kathmandu valley. Kathmandu Valley.

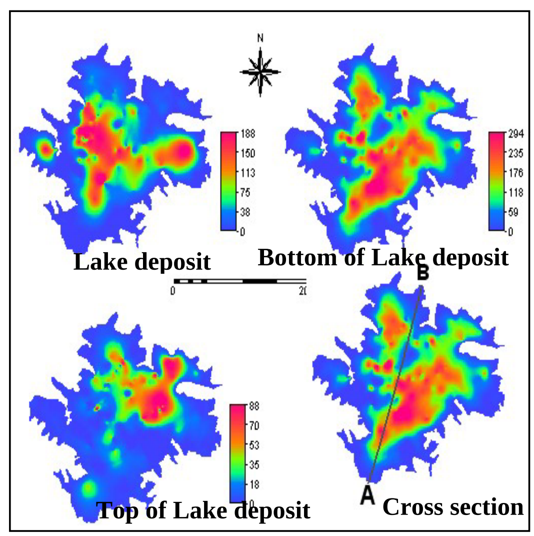


Fig. 6: Thickness maps generated for the Four-layer model for

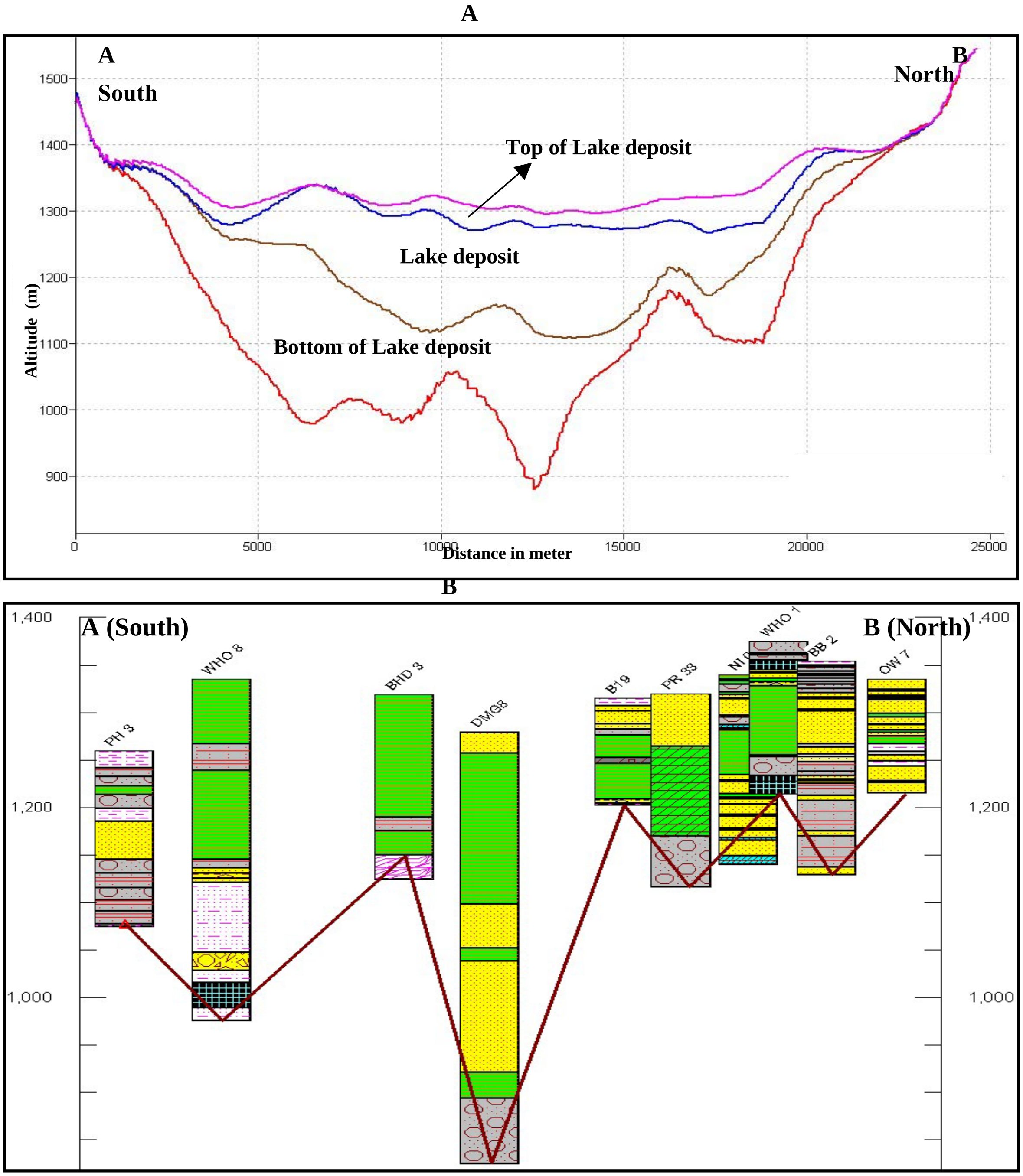


Fig. 7: Example of a cross section.(See Figure 4.8 D for the location).
A: cross section generated from the simplified layer model.
B: corresponding borehole logs for the same area.

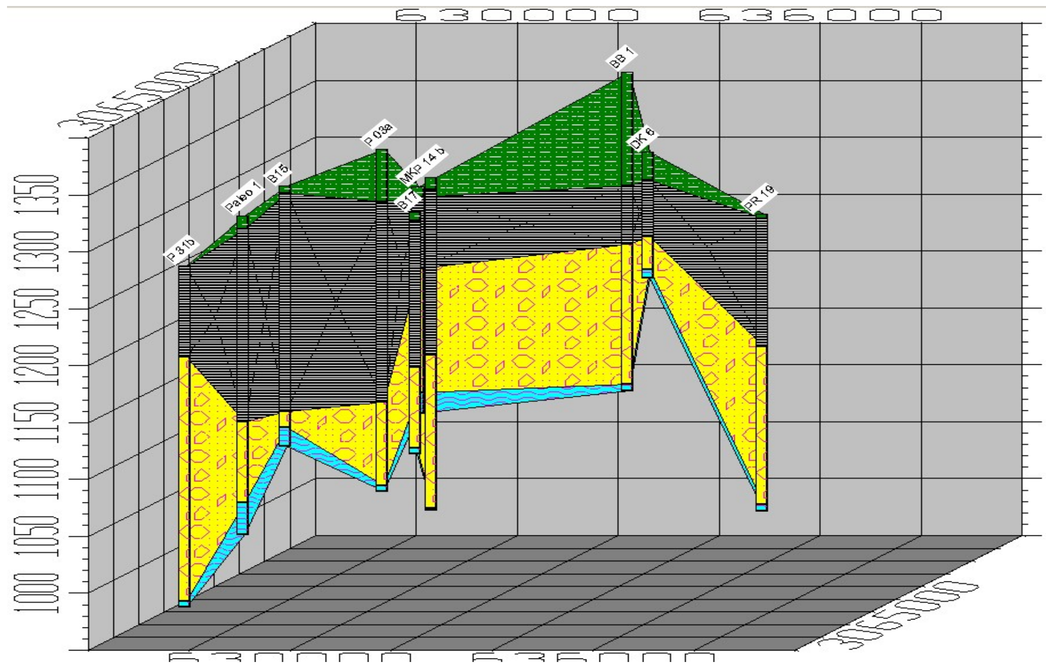


Fig. 8: Fence diagram of different lithologs

## Stratigraphic profile along West – East direction

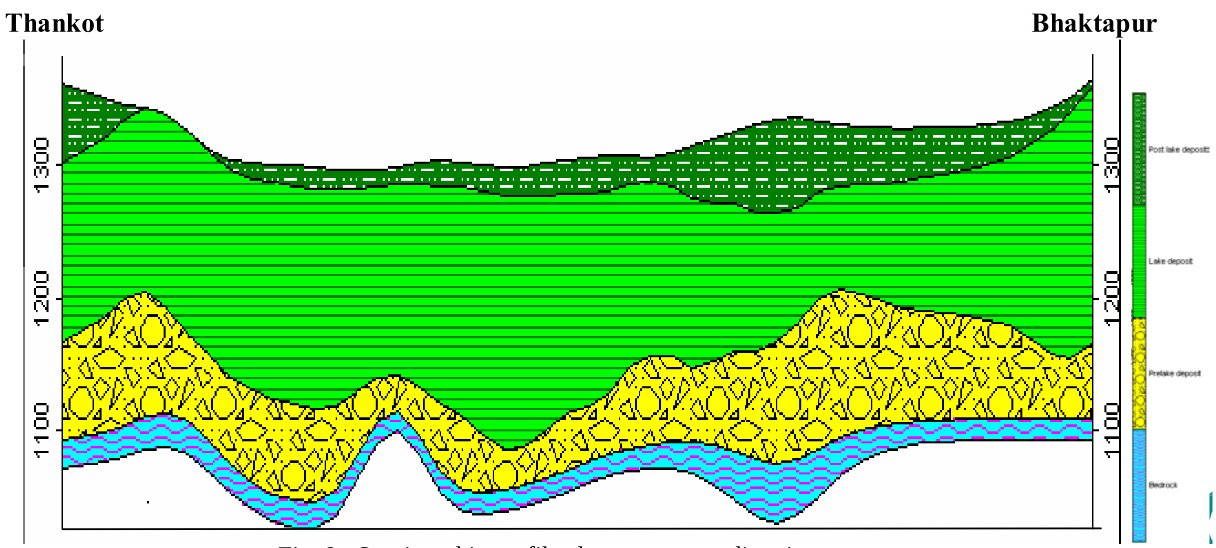


Fig. 9: Stratigraphic profile along west-east direction

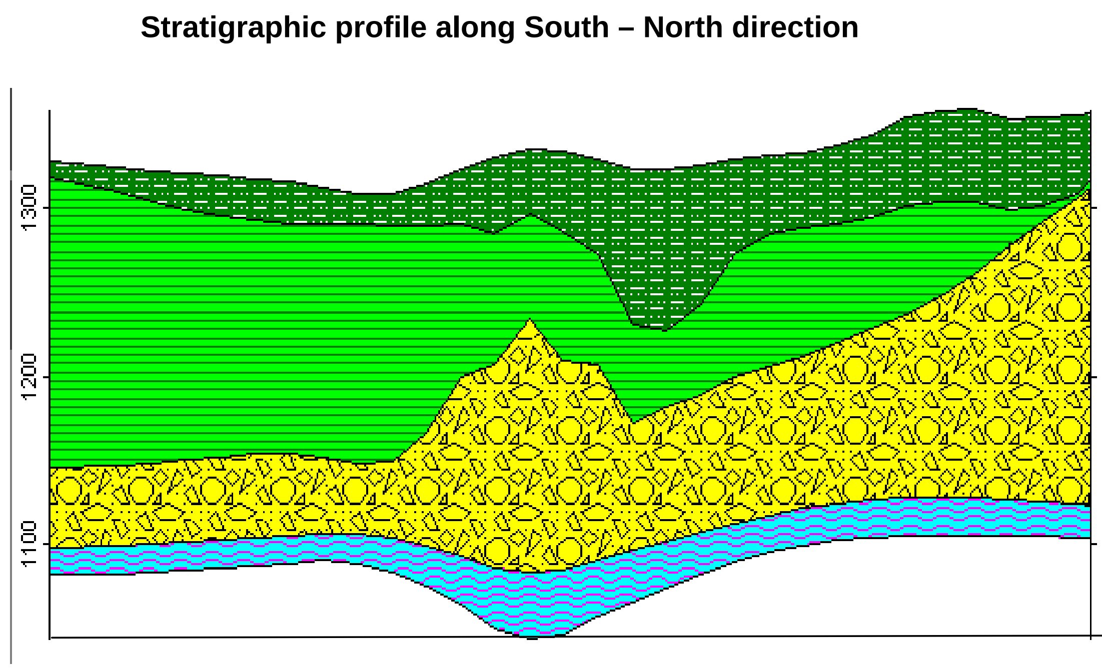


Fig. 10: Stratigraphic profile along north-south direction

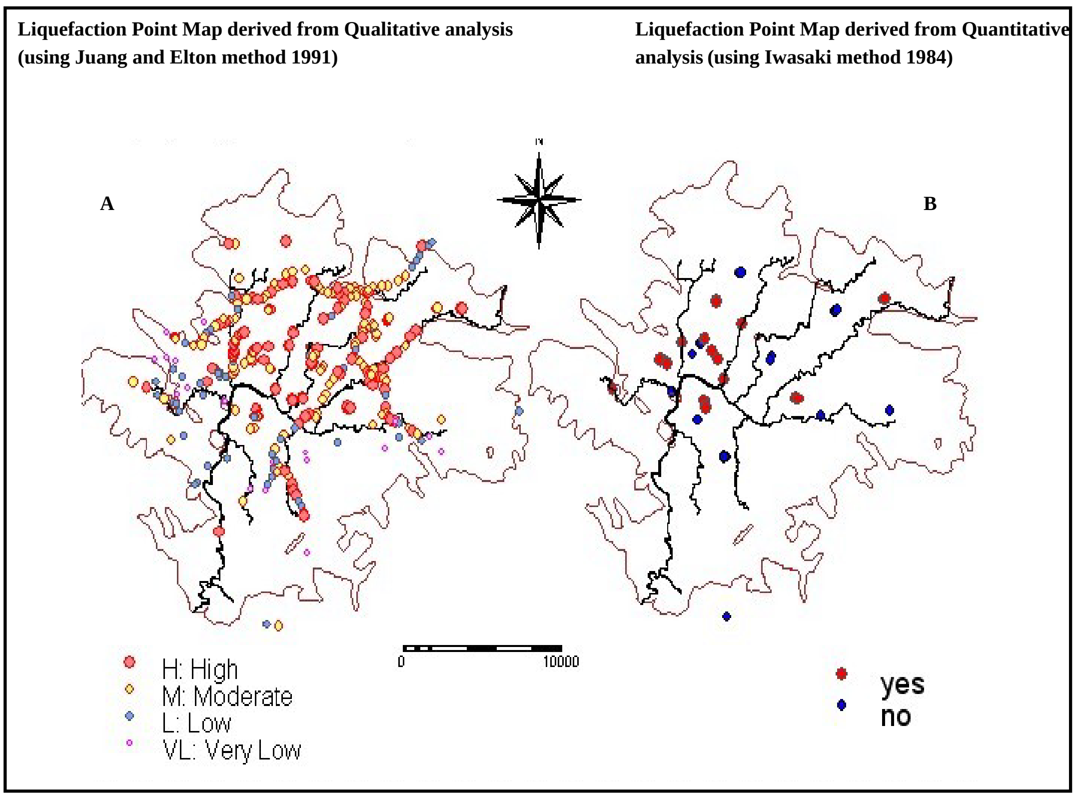


Fig. 11: Classified borehole point maps A. Qualitative method, B. Quantitative method

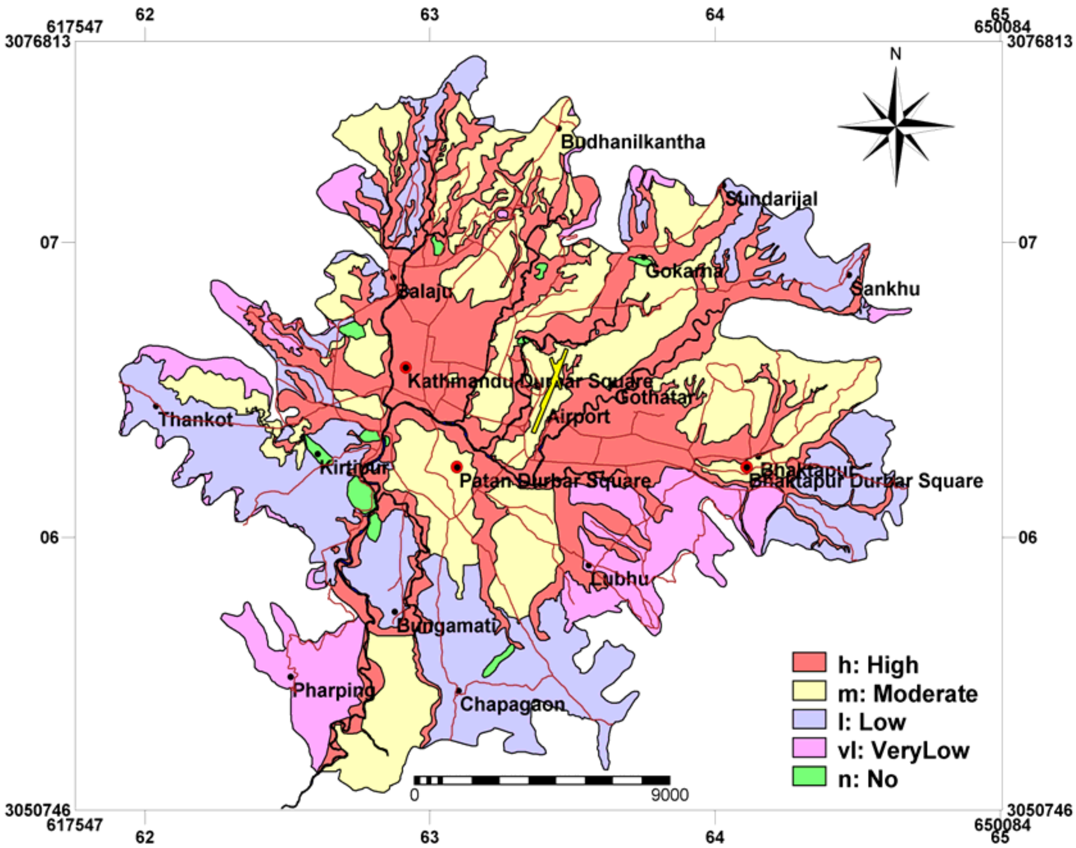


Fig. 12: Liquefaction susceptibility map of the Kathmandu valley