# Highlights

## An assessment of geographical accessibility to COVID-19 testing in Nepal

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- Descriptive analysis of the Covid-19 laboratory coverage in Nepal during 2021
- Preview of the potential of optimized locations
- Relation with relative population wealth

# An assessment of geographical accessibility to COVID-19 testing in Nepal★

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ABSTRACT

Ensuring equitable physical access to SARS-CoV-2 testing has proven to be crucial for controlling the COVID-19 epidemic, especially for countries such as Nepal with its challenging terrain. During the second wave of the pandemic in May 2021, there was immense pressure to expand the laboratory network in Nepal to ensure calibration of epidemic response. This resulted in an increase in the number of testing facilities from 69 laboratories in May 2021 to 89 laboratories by November 2021.

Based on up-to-date publicly available data sets, we measured the disparities in geographical accessibility to COVID-19 testing across Nepal at $1 \times 1$ km$^2$ resolution. The analysis identifies vulnerable districts where, despite ramping up efforts, physical accessibility to testing facilities remains low under two modes of travel – walking and motorized driving.

In addition, an optimization model is proposed to prescribe the best possible locations in Nepal to set up testing laboratories for maximizing access by its population. Both geographical accessibility and its equality were better under the motorized mode compared with the walking mode. If motorized transportation were available to everyone, the population coverage within 60 minutes of any testing facility (public and private) would be close to threefold the coverage for pedestrians within the same hour.

Very low accessibility was found in most areas except those with private test centers concentrated in the capital city of Kathmandu. In mountainous terrain, accessibility was very low and could not improve even if considering all the existing healthcare facilities as potential testing locations.

The high-resolution analysis of geographical accessibility to COVID-19 testing facilities based on an openly available data stack should provide valuable information for health-related planning in Nepal, especially in emergencies where data might be limited and decisions time-sensitive.

## Evidence before the study

To the best of our knowledge (we searched Google Scholar, and Scopus databases using terms such as “Healthcare equity in pandemic response”, “COVID-19 testing accessibility”, “Geographical analysis of healthcare facilities”, and “Optimization of COVID-19 testing locations”), literature on the importance of equitable access to healthcare facilities has mainly focused on urban or densely populated regions, often at a lower resolution at different administrative levels

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such as counties or provinces. Strategies to optimally invest in public health infrastructure like COVID-19 testing laboratories did not explore the use of high-resolution globally available open datasets coupled with official country datasets and application program interfaces (APIs) for near-real-time travel time computations. Such an approach is especially relevant for regions with challenging and diverse terrain such as Nepal.

Previous studies on healthcare accessibility during the COVID-19 pandemic did not look at how socioeconomic factors influence access to testing facilities. To start addressing this gap, our study used the relative wealth index which is a globally available open dataset as a proxy indicator to understand disparities in access due to economic factors.

### Added value of this study

This study uniquely contributes by employing publicly available global data sets coupled with publicly available official data sources from the country, to assess COVID-19 testing accessibility in Nepal considering the location of population households at a $1 \times 1$ km$^2$ resolution and the estimated headcounts of those households. In addition, the study uses state-of-the-art realistic travel time calculations and includes both walking and motorized travel modes. The use of open data enhances the replicability and applicability of the findings in similar contexts globally. We employed a mathematical optimization model, solved with Gurobi Optimization, LLC (2023), to identify the optimal locations for additional testing laboratories in Nepal, maximizing population coverage while considering the heterogeneity in relative wealth as a proxy indicator for transportation availability. We publish our code and all data used to produce this article openly on Analytics for a Better World (2023).

### Implications of all available evidence

Our study highlights the need for a more equitable distribution of COVID-19 testing facilities in Nepal. Our findings suggest that accessibility is particularly low in mountainous regions and areas with lower relative wealth. This highlights the importance of considering transportation availability and the heterogeneity of population density when planning for testing infrastructure. Our study also aligns with WHO guidelines for establishing a tiered laboratory network that ensures geographical coverage and equity in testing access. Using open globally available data and mathematical optimization approaches facilitates replicability and provides a valuable tool for health-related planning not only in Nepal but also globally in resource- and time-constrained emergencies where data is often scarce.

## 1. Introduction

The COVID-19 pandemic led countries to implement various response measures to protect their populations' health. Among these measures are testing strategies to monitor the spread of the disease in different regions, which help inform interventions like promoting social distancing (Sharma and Bhatta (2020); Bourassa, Sbarra, Caspi and Moffitt (2020)) and restricting travel. However, mobility restrictions can hinder access to testing if testing facilities are not widely available. In Nepal, as of November 2021, a total of 89 laboratories were operational, each serving only the population within its respective province. These laboratories were either government-owned or privately operated. An alternative to fixed testing facilities is the use of mobile laboratories, which can take different forms (World Health Organization (2021)). Mobile laboratories offer additional capacity and flexibility to meet varying testing demands, as they can be relocated based on the spread of the infection. However, during a prolonged incident like the COVID-19 pandemic, decisions regarding their deployment can be challenging. Moreover, the distribution of these facilities should contribute to a service network that aims to be accessible to a significant portion of the population. However, since the concept of accessibility refers to the population's ability to reach goods or services, whether commercial (restaurants, shops, etc.) or social (education and medical services), there is no single, definitive definition of the concept.

The importance of ensuring equitable access to healthcare facilities, as well as the current situation in Nepal, has been assessed by Cao, Shakya, Karmacharya, Xu, Hao and Lai (2021). While their study focuses on the overall state of affairs, ours specifically examines the availability of SARS-CoV-2 testing laboratories during the response to the COVID-19 pandemic.

Reviews (Geurs, Ritsema van Eck and voor Volksgezondheid en Milieuhygieëne (Netherlands) (2001); Geurs and van Wee (2004); Tariverdi, Nunez-del Prado, Leonova and Rentschler (2023)) of accessibility measures state that they should consider the cost individuals incur to travel to the service location, as well as the number and distribution of opportunities, particularly in relation to the spatial distribution of these opportunities. In particular, travel cost models suggest that the greater the time or distance required to reach a destination, the less accessible that destination becomes.

Similarly, Wang (2011) state that important elements of an accessibility measure include the number of opportunities for clients to access a service, the costs associated with traveling to meet the demand, and a measure of spatial segregation, which aims to define an inclusive service network that avoids excluding regions within the potential service area (especially crucial in the case of pandemics). Therefore, several indicators can be defined to represent key characteristics of an accessibility measure.

In light of these considerations, our study aims to: i) assess the geographical distribution of COVID-19 testing facilities in Nepal, ii) define the accessibility of these laboratories, and iii) utilize mathematical optimization approaches to maximize population coverage, considering the heterogeneity in relative wealth as a proxy indicator for transportation availability to reach the laboratories.

Furthermore, Nepal's challenging geography (ICIMOD (2022)) necessitates measuring accessibility by accounting for actual travel times. After a careful comparison, validated by colleagues in the field, we selected MapBox (2022) as the provider of accurate distances and travel times using the local road infrastructure while reflecting the geography and average traffic conditions to use for this study.

## 2. Materials

### 2.1. COVID-19 Laboratories

The data on COVID-19 laboratories and the date they became operational, as used in this study, were taken from the daily situation reports published by Nepal's Ministry of Health and Population (MoHP) Ministry of Health & Population (2022). These reports detail how Nepal's diagnostic network responded to the SARS-CoV-2 pandemic. Besides data on the numbers and distribution of cases and deaths across the country, the reports also provide details on the number of PCR tests each laboratory performed daily. For a discussion on the burden imposed by the pandemic on the different laboratories, including the frequency of visits and testing and the stress on the laboratories' capacity, we refer to Bakker, Govindakarnavar, Gromicho, Krishnan, del Rio Vilas, Samuel, Jha, Shrestha, Mulmi, Bhusal, Stapith, Jha and Shrestha (2024). For the study of this article, we extract the evolution of the diagnostic network in response to the pandemic activity as well as the contribution of individual laboratories to providing the population with diagnostic testing. While MoHP provides situation reports since the beginning of the pandemic (January 28$^{\text{th}}$, 2020), we restrict our analysis to the period between May 1$^{\text{st}}$, 2021, and November 15$^{\text{th}}$, 2021. The reason for this is twofold. Firstly, for the considered period, we have consistent data reporting. Secondly, the period includes several operationally relevant phases about the pandemic activity and testing capacity development, e.g., in May and June 2021, the "second wave" led to the biggest surge in infections up to this point, triggering yet another phase of establishing new laboratories across the country in response.

### 2.2. Vulnerability of Population

In this study, we utilized the relative wealth index data from Data For Good - Meta (2017). The relative wealth index is a metric that predicts the relative standard of living within countries using privacy-protecting connectivity data, satellite imagery, and other innovative data sources. It is constructed by incorporating nontraditional data sources, such as satellite imagery and privacy-protected Facebook connectivity data. The index's accuracy is verified through comparison with ground truth measurements from the Demographic and Health Surveys. On a global scale, there are approximately 20 million micro-regions, each covering an area of 2.4 km$^2$. The relative wealth index provides an estimation of the wealth level of individuals residing in each micro-region in relation to others within the same country.

Detailed in Chi, Fang, Chatterjee and Blumenstock (2022), the Relative Wealth Index is a statistical measure used to estimate the economic status or wealth of households within a population. It is derived from asset ownership and living conditions data, using methods such as principal component analysis (PCA) to aggregate multiple indicators into a single index. The index typically does not have a fixed scale; instead, it is often standardized around a mean of zero. Higher values indicate greater wealth, while lower values indicate poorer conditions. The scale and range can vary depending on the data and the specific method of calculation. Higher values, above zero, indicate households that are wealthier than the average. These households likely own more assets and have better living conditions. Lower values, below zero, represent households that are less wealthy than the average, with fewer assets and inferior living conditions.

The index allows comparisons across different geographic areas or demographic groups within a study, providing insights into the distribution of wealth and its impact on various outcomes like health, education, and access to services. It is particularly useful in environments where direct monetary measurements are difficult to obtain. This metric is instrumental for policymakers and researchers in identifying disadvantaged areas and populations, helping to tailor interventions and allocate resources more effectively.

# 3. Methods

## 3.1. Facility Catchment Area and Population Covered

To ensure realistic travel times, our study takes into account the country's existing infrastructure, such as roads and streets and whether these are for pedestrian and/or motorized access. We rely on reputable services that estimate travel times based on real-life data, and we validated their accuracy through consultation with local experts. After comparing OSM, Google, Microsoft Here, and MapBox and confirming a selection of representative travel times with local knowledge, we selected MapBox as our preferred provider for the acknowledged accuracy in the field.

For calculating travel times within specified time frames, we utilized the isochrone API Mapbox (2024) from MapBox (2022). This API generates contour lines or vector representations of the reachable area for walking and driving modes. Our analysis included four isochrones: 30 minutes for both walking and driving, as well as 60 minutes for walking and driving.

Accessibility is measured by considering the distance and average time required for walking and driving, utilizing the local road infrastructure and a wealth of data. To assess population access, we established the four isochrones for each of the 89 existing laboratories, as described above. Each household was categorized accordingly to being part of those isochrones or not, enabling us to calculate coverage based on the headcounts corresponding to the households. Coverage represents the percentage of the population with access to at least one laboratory within the specified time threshold. We calculated coverage for two scenarios: i) the actual scenario where testing was only allowed within the province of residence, and ii) a scenario where movement between provinces was permitted.

## 3.2. Optimization Model

Our optimization model is based on the classical maximum coverage location problem Church and ReVelle (1974). In this problem, we specify the desired number of laboratories and assess the number of households within the catchment area of each potential laboratory location. We assign a weight to each household, reflecting its headcount. The model then selects locations in such a way that the combined population within their catchment areas has the highest weight, maximizing the coverage (represented by the highest headcount of the population served within the joint catchment area). Such a model translates the decisions (which laboratories to open), the objective to meet (highest possible coverage of the population within the agreed metric), and the constraints (respect a budget, i.e. a maximum number of laboratories, choose from suitable candidates, consider covered the households that are within the agreed metric of an open laboratory) into a mathematical formulation that a specific solver can handle. Once instanced with the relevant data, the resulting problem is solved to optimality, meaning the choice of laboratories that achieves the highest possible coverage. We used Gurobi Optimization, LLC (2023) to solve these so-called 'mixed integer linear optimization problems' to optimality. In our case, the main decision is which subset of the potential sites to select for opening laboratories. To formalize the model, we need the following sets and parameters:

- $I$ - the set of households, obtained as described in 9.1.4. These are a total of 136 093 individual points, as result of an aggregation to adjacent squares of 1km$^2$. Only the squares with a positive joint headcount are used.
- $J$ - the set of potential health care facilities, obtained as described in 9.1.5. These are 1 682 locations in Nepal. For each of those, the four isochrones described in 3.1 were computed using Mapbox (2024) as described in 9.1.2.
- $J_i$ - the set of potential health care facilities within reach of household $i \in I$. Note: $J_i \subseteq J$. This is obtained using the isochrones from 9.1.2 in the following manner: if household $i$ is inside the isochrone $j$ for the metric considered, then $j \in J_i$.
- $w_i$ - the weight of each household $i \in I$, its headcount. This is also from 9.1.4 and reflects the same aggregation as when defining $I$. It sums to 29 135 247 inhabitants on our dataset.

Each of the four metrics used leads to one instance of the problem, as the metric defines the sets $J_i$. The model revolves around binary decision variables $z_i$ for each household $i \in I$ to indicate if that household can be served by a health care facility that is opened at $j \in J$, as indicated by the corresponding variable $x_j$. In that case, the household is covered and its headcount counts for the objective function value of the solution.

The complete model, as formulated below, states in the first line the objective as to maximize the total weight of the households served, while the second line (after subject to:) lists the first constraint: each household is only served if at least one laboratory within reach is open. Then the number of laboratories to open is limited by $p$, a parameter that indicates the maximum number of locations to select.

$$
\begin{aligned}
\max \quad & \sum_{i \in I} w_i z_i & \\
\text{subject to:} \quad & z_i \leq \sum_{j \in J_i} x_j & \forall i \in I \\
& \sum_{j \in J} x_j \leq p & \\
& x_j \in \{0, 1\} & \forall j \in J \\
& z_i \in \{0, 1\} & \forall i \in I
\end{aligned}
$$

The next subsections explain the two levels of decision-making that this mathematical optimization model helps to address.

### 3.3. Pareto curves for strategic decisions

To address the decision of how much budget to allocate for the expansion, which translates into the number of new laboratories to open, one needs to balance the costs and the benefits. In our case, the costs relate to opening new laboratories and are bounded by the available budget, which leads to $p$. The benefits are the percentage of the population with access to at least one laboratory. Plotting the coverage obtained against the number of facilities added leads to a Pareto frontier that shows the optimal value of the optimization problem defined above as a function of the parameter $p$, defining the budget to spend. To obtain such curves we need to solve the optimization problem with increasing values of $p$. For that reason, unlike Church and ReVelle (1974), we model the budget constraint as an inequality, while originally the model was proposed with equality. The reason is technical: the solution obtained for $p$ remains feasible for $p + 1$ enabling the solver to start with a valid solution in its search for a new optimum. These so-called 'hot starts' often decrease the time taken by the solver to find the optimal solutions.

### 3.4. Incremental optimization for tactical deployment

It is important to note that the optimal solution to add, for example, 10 additional facilities may not necessarily be a subset of the optimal solution to add 11 additional facilities. Therefore, this Pareto frontier does not indicate the specific facilities that will open over time. To define a good order for opening the laboratories, ensuring the highest gain at each step toward the optimal solution selected, we create a sequence of facilities to be added over time, leading to that optimal selection. For this purpose, we utilize a simple greedy algorithm applied to the sub-problem that consists only of the facilities in the optimal solution: at each step select the laboratory that yields the highest increment in coverage among all not yet opened laboratories in the optimal selection. This approach ensures effective and efficient implementation of facility additions over time.

## 4. Results

We use color-coded figures to aid in presenting our results. We consistently use colors from two important sets, presented in Figure 1: colors used to distinguish the access metrics and colors used to identify the country's province. Additional colors are used and explained for specific purposes.

### 4.1. Descriptive analysis

Nepal has a very challenging geography, with elevations ranging from less than 100 meters to over 8,000 meters above sea level. A visual representation is provided in Figure 1, including on the right-hand side a map with the laboratory locations on the whole of Nepal, color-coded according to the respective provinces. This map is shown on a background that depicts the mountainous characteristics of the ground, the differences in elevation being more frequent in the north than the south of the country. The letter, G or P, inside the pin locating each laboratory denotes a Government or Privately owned laboratory, respectively. Most of the laboratories are concentrated in and around the capital city of Kathmandu, identified by the nation's flag. It should be noted that the areas for one-hour driving, while remaining in the same province as the laboratory is situated, are also depicted in the right part of the figure, clearly

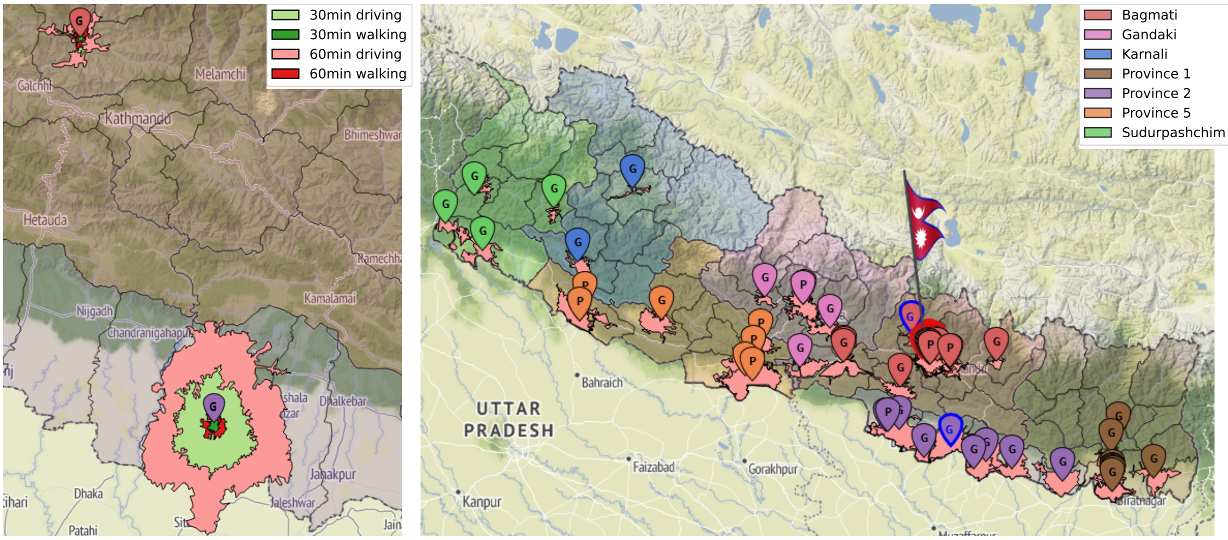



**Figure 1:** On the right, the geographical distribution of the laboratories (Government and Private) as of November 2021, including the catchment areas of one-hour motorized traveling: the pale red polygons with a black boundary encompass the points within that travel time of the pin in their middle. Administrative areas and laboratory pins are colored to identify the seven provinces of Nepal. On the left, we zoom in on two laboratories and compare the catchment areas for the four metrics of travel times. These laboratories are identified with a blue border around their pins on the right and are situated at different elevations, clearly showing how geography affects travel times.

| Province | Laboratories | Government owned | Privately owned | Inhabitants | Laboratories per million inhabitants |
|---|---|---|---|---|---|
| Bagmati | 50 | 19 | 31 | 7 783 878 | 6.42 |
| Gandaki | 6 | 5 | 1 | 1 691 668 | 3.55 |
| Karnali | 2 | 2 | 0 | 1 078 543 | 1.85 |
| Province 1 | 9 | 5 | 4 | 5 974 835 | 1.51 |
| Province 2 | 9 | 8 | 1 | 5 648 457 | 1.59 |
| Province 5 | 9 | 4 | 5 | 3 720 260 | 2.42 |
| Sudurpashchim | 4 | 4 | 0 | 3 237 606 | 1.24 |
| Nepal | 89 | 47 | 42 | 29 135 247 | 3.05 |

**Table 1**
Number of laboratories by province, their ownership, as well as the number of inhabitants and the number of laboratories per million inhabitants.

demonstrating that large portions of the Nepal surface do not have access to a laboratory within a one-hour drive. Only the population that resides inside such areas has the corresponding access. On the left-hand side of Figure 1 we show the two laboratories whose pin has a blue boundary on the right. These were chosen to illustrate the impact of geography on accessibility. The top one, Trishuli Hospital in Bidur, north-west of Kathmandu, is at just 600 meters above sea level, but on an already mountainous area, while the one on the bottom, Malangawa Hospital, south-east of Kathmandu, is at 100 meters on a mostly flat area. Notice the respective areas of points within the four access metrics of traveling time to that laboratory. The area encompassed by the figure delimiting the one-hour drive is 104.4 $km^2$ around Trishuli Hospital in Bidur, and 1 843.8 $km^2$ around the Malangawa Hospital. Note that to show more clearly the effect of geography, independently of the administrative constraints, the one-hour drive area is not delimited to the province or even country boundaries on the left-hand side figure. We believe this visualization helps us understand the importance of accurate accessibility metrics, such as the ones adopted by this work.

### *4.1.1. Situation in November 2021*

Of the 89 laboratories that were operational in November 2021, 30 were in Kathmandu (shown in Figure 1 with a red boundary around their pin). Observe that these pins overlap due to the small confinement on the nation's scale.

While Bakker et al. (2024) addresses the burden imposed by the pandemic on the different laboratories, including the frequency of visits and testing and the stress on the laboratories' capacity, we focus this work on the strategic decisions of where to locate laboratories based on the location and density of the population and the real-life accessibility efforts. These decisions are taken at an earlier moment, to enable installation and deployment. As of November 2021, the average number of laboratories per million inhabitants in Nepal was approximately 3. Table 1 illustrates the distribution of laboratories per province, revealing noticeable heterogeneity. Bagmati province, for instance, offers more than 6 laboratories per million inhabitants, while Sudurpashchim province has only 1.

### 4.1.2. *From May 2021 to November 2021*

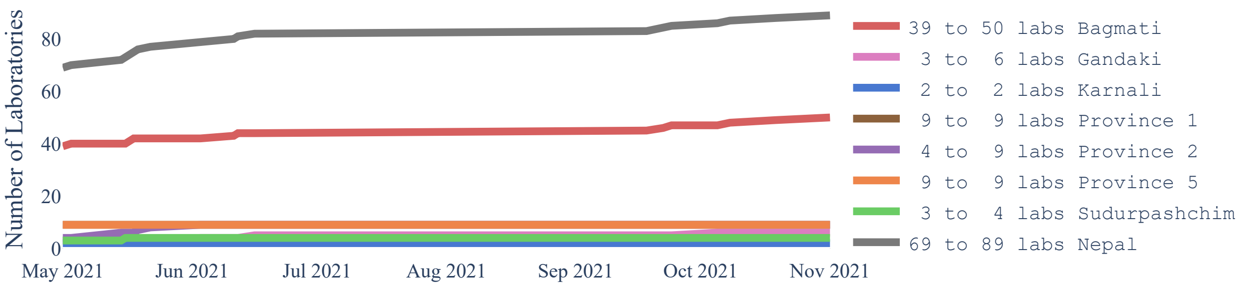



**Figure 2:** Number of COVID-19 laboratories in Nepal and per province from May 2021 to November 2021

Figure 2 shows the increase over time in the number of laboratories from May to November 2021 in each province and the whole country, The increases are on the actual dates that laboratories were added. Figure 3 and Figure 4 show how the coverage, measured by each metric, increased in the whole of Nepal from May to November 2021. Figure 3 reflects the case when access is restricted to the laboratories in the same province, while Figure 4 shows a slight overall increase in accessibility if we remove the constraint of visiting laboratories within the province of residence. In particular, at the end of the period, 61.4% of the population had access to a testing laboratory within a motorized traveling time of one hour while walking just 22.2% of the population can reach a laboratory within one hour. Relaxing the 'same province' access restriction would have increased access both at the start of the period, in May, and at the end, in November.

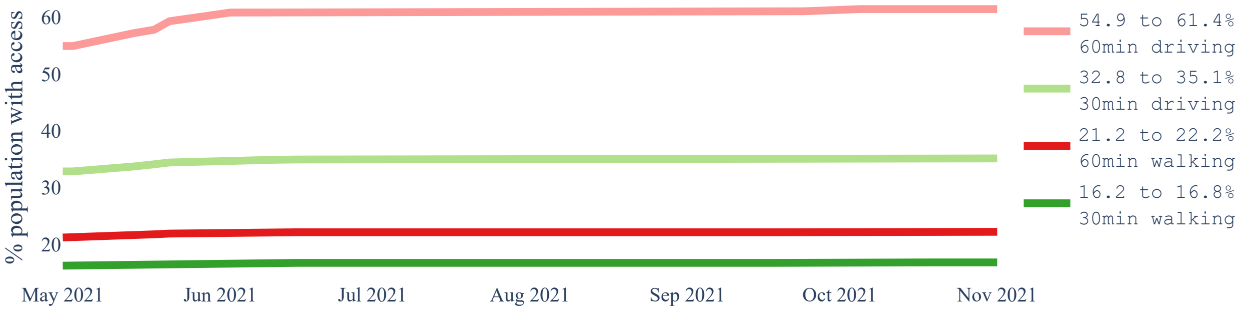



**Figure 3:** The proportion of the population with access to at least one laboratory within the stated threshold in the province of residence from May 2021 to November 2021

The effect of relaxing the 'same province' constraint is the largest for laboratories close to province boundaries, see Figure 5 for such an example. The changes are higher for the original 69 laboratories than for the final 89, meaning that, if at all possible, relaxing the administrative constraint would already have increased accessibility in May 2021.

## 4.2. Effect of restricting access to the same province at district level

Considering the situation with respect to the 89 laboratories in operation from November 2021 as shown in Figure 1, figures 6 and 7 show the accessibility by district for the two scenarios: restricted testing within the province, and not restricted. The latter returns a larger number of districts with access to at least 1 laboratory within the travel

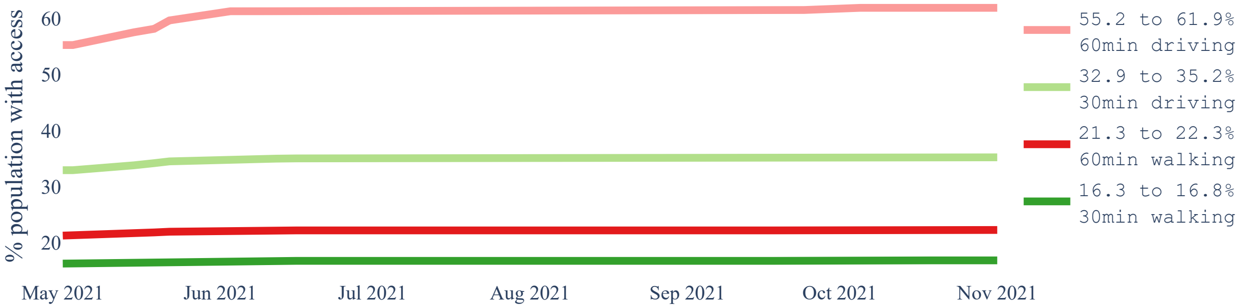



**Figure 4:** The proportion of the population with access to at least one laboratory within the stated threshold regardless the province of residence from May 2021 to November 2021

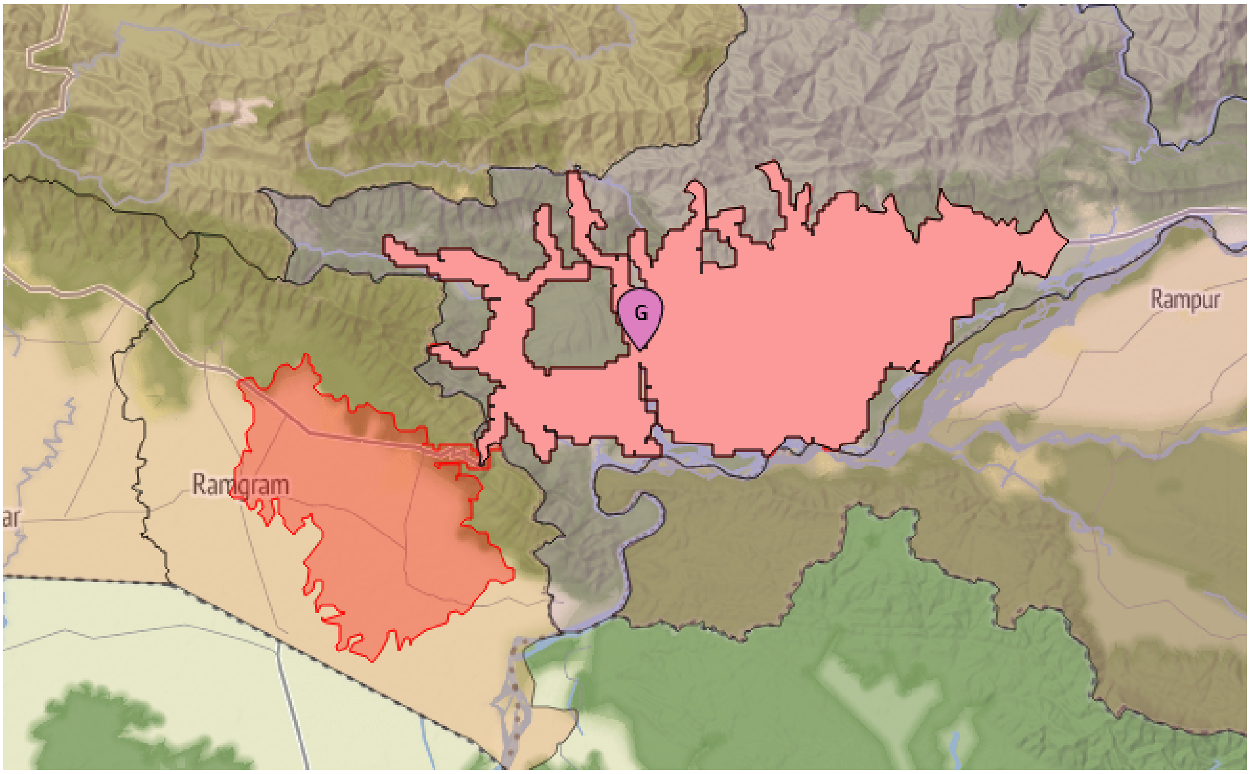



**Figure 5:** Madhyabindu Hospital in province Gandaki could serve additional 128 192 individuals within 60 minutes of driving time from Province 5, as shown by the left part, the translucid one, of the isochrone. Both parts are connected by the East-West Highway NH01.

time thresholds. Tables 2 and 3 show a summary of the access in the same restricted and unrestricted cases. If only laboratories in the same province can be visited, and we consider 60 minutes of driving time then 26 out of the 77 Nepalese districts have no access at all. These districts are: Arghakhanchi, Baitadi, Bajhang, Bajura, Bhojpur, Dailekh, Darchula, Dolpa, Humla, Jajarkot, Kalikot, Khotang, Manang, Mugu, Mustang, Okhaldhunga, Panchthar, Pyuthan, Ramechhap, Rukum E, Rukum W, Salyan, Sankhuwasabha, Sindhuli, Solukhumbu and Taplejung. By relaxing the province constraint districts Dailekh and Salyan, both from the province Karnali, gain access, lowering the number to 24.

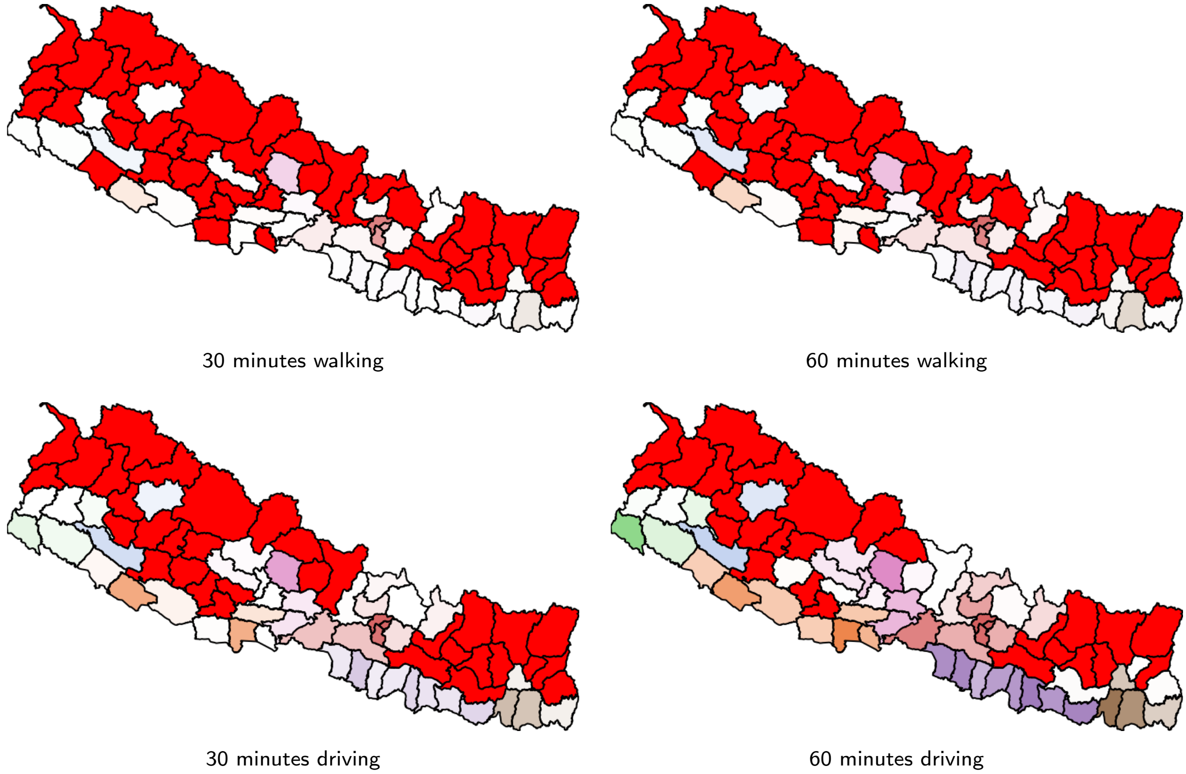



**Figure 6:** Accessibility per district to the closest, restricted, laboratory. The colors relate to the province color with darker colors indicating greater accessibility. Red is used to show the districts with no accessibility at all.

| | 60min driving | | | | 30min driving | | | | 60min walking | | | | 30min walking | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Province | % | # | min | max | % | # | min | max | % | # | min | max | % | # | min | max |
| Bagmati | 82.69 | 2 | 2.07 | 100.00 | 74.98 | 2 | 0.01 | 96.50 | 67.60 | 5 | 3.52 | 91.00 | 56.35 | 5 | 1.00 | 78.10 |
| Gandaki | 40.30 | 2 | 0.44 | 89.80 | 21.67 | 4 | 0.03 | 71.60 | 11.82 | 7 | 0.69 | 48.10 | 7.97 | 7 | 0.29 | 34.00 |
| Karnali | 5.89 | 8 | 0.22 | 31.20 | 4.07 | 8 | 0.15 | 24.00 | 2.58 | 8 | 0.10 | 15.70 | 0.99 | 8 | 0.04 | 6.80 |
| Province 1 | 59.41 | 7 | 0.45 | 87.60 | 28.08 | 10 | 5.76 | 41.80 | 6.39 | 10 | 1.31 | 24.60 | 2.32 | 10 | 0.40 | 14.10 |
| Province 2 | 73.58 | 0 | 14.27 | 89.40 | 19.84 | 0 | 3.85 | 36.20 | 6.29 | 0 | 1.22 | 12.40 | 2.16 | 0 | 0.42 | 4.30 |
| Province 5 | 50.73 | 3 | 0.45 | 99.10 | 23.96 | 5 | 0.48 | 69.30 | 5.29 | 8 | 0.67 | 31.90 | 2.30 | 8 | 0.29 | 16.10 |
| Sudurpashchim | 34.65 | 4 | 1.02 | 75.00 | 9.04 | 4 | 0.13 | 16.40 | 1.16 | 5 | 0.10 | 2.10 | 0.42 | 6 | 0.05 | 0.60 |
| Nepal | 61.43 | 26 | 0.44 | 100.00 | 35.11 | 33 | 0.01 | 96.50 | 22.18 | 43 | 0.10 | 91.00 | 16.79 | 44 | 0.29 | 78.10 |

**Table 2**
Detailed coverage if only laboratories in the same province can be visited. Each sub-table per access metric lists 4 values per province in this order: the percentage of the population in the province with access to at least one laboratory, followed by the number of districts where no single person can access a laboratory and the minimum and maximum percentage of access per district in that province.

## 4.3. Equality

We now extend the previous analysis considering the relative wealth index to inform equality in accessibility. We used micro-estimates of relative wealth at a 2.4-kilometer resolution from Data For Good - Meta (2017) to compute the median relative wealth at the district level. While we decided to consider households in the same district as having the same relative wealth in our work, other choices could be made, however since other choices would require validation, we opted for simplicity.

To visualize the situation we use scatter plots where the size of the dots reflects the population size of the district it represents, colored by the province it belongs to. Each dot is placed according to the median relative wealth index of the population in the corresponding district and the coverage: the percentage of the population within the district with access to at least 1 laboratory, either within or across provinces as indicated in each legend.

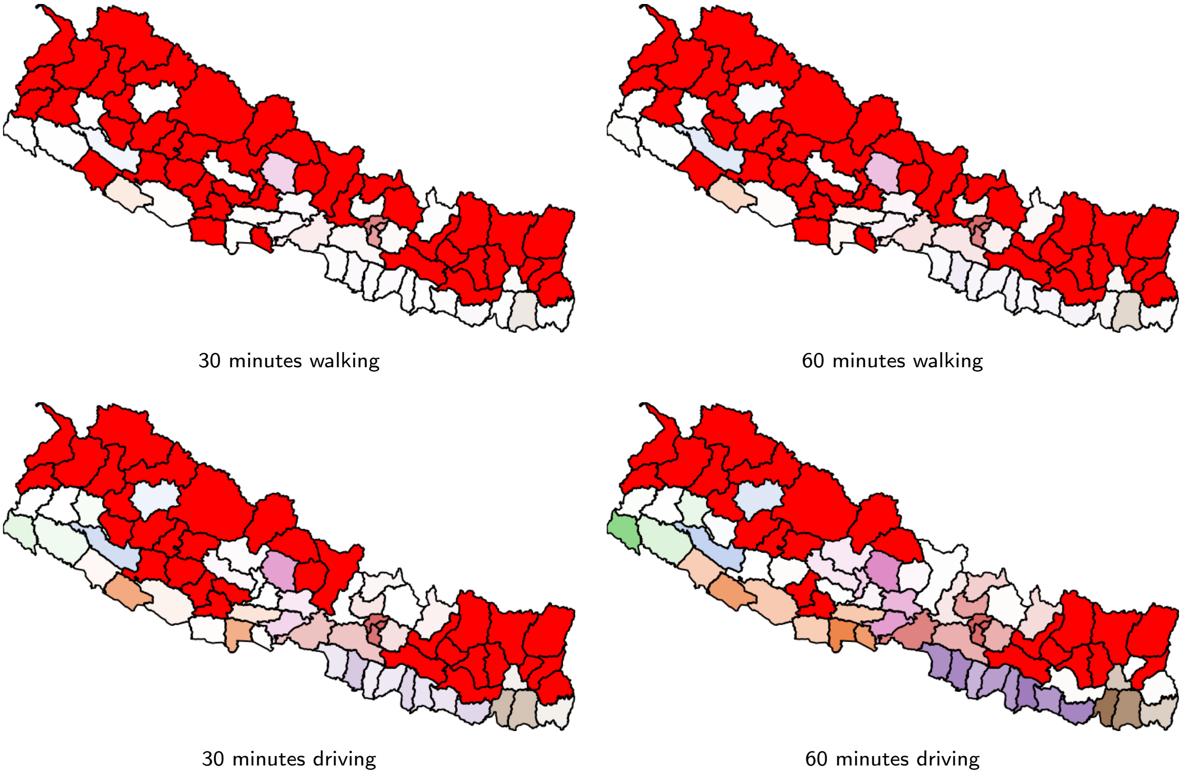



**Figure 7:** Accessibility per district to the closest, unrestricted, laboratory. The colors relate to the province color with darker colors indicating greater accessibility. Red is used to show the districts with no accessibility at all.

| | 60min driving | | | | 30min driving | | | | 60min walking | | | | 30min walking | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Province | % | # | min | max | % | # | min | max | % | # | min | max | % | # | min | max |
| Bagmati | 82.69 | 2 | 2.07 | 100.00 | 74.98 | 2 | 0.01 | 96.50 | 67.60 | 5 | 3.52 | 91.00 | 56.35 | 5 | 1.00 | 78.10 |
| Gandaki | 43.64 | 2 | 0.69 | 89.80 | 23.32 | 4 | 0.03 | 71.60 | 13.14 | 7 | 0.76 | 48.10 | 8.67 | 7 | 0.29 | 34.00 |
| Karnali | 6.35 | 6 | 0.02 | 31.20 | 4.07 | 8 | 0.15 | 24.00 | 2.58 | 8 | 0.10 | 15.70 | 0.99 | 8 | 0.04 | 6.80 |
| Province 1 | 59.64 | 7 | 0.45 | 88.00 | 28.08 | 10 | 5.76 | 41.80 | 6.39 | 10 | 1.31 | 24.60 | 2.32 | 10 | 0.40 | 14.10 |
| Province 2 | 73.60 | 0 | 14.27 | 89.40 | 19.85 | 0 | 3.85 | 36.30 | 6.29 | 0 | 1.22 | 12.40 | 2.16 | 0 | 0.42 | 4.30 |
| Province 5 | 52.27 | 3 | 0.45 | 99.10 | 24.00 | 5 | 1.12 | 69.30 | 5.29 | 8 | 0.67 | 31.90 | 2.30 | 8 | 0.29 | 16.10 |
| Sudurpashchim | 34.65 | 4 | 1.02 | 75.00 | 9.04 | 4 | 0.13 | 16.40 | 1.16 | 5 | 0.10 | 2.10 | 0.42 | 6 | 0.05 | 0.60 |
| Nepal | 61.88 | 24 | 0.02 | 100.00 | 35.21 | 33 | 0.01 | 96.50 | 22.25 | 43 | 0.10 | 91.00 | 16.83 | 44 | 0.29 | 78.10 |

**Table 3**
Detailed coverage if laboratories can be visited regardless of the province. Each sub-table per access metric lists 4 values per province and per accessibility metric, in this order: the percentage of the population in the province with access to at least one laboratory, followed by the number of districts where no single person can access a laboratory and the minimum and maximum percentage of access per district in that province.

We add the linear trendlines corresponding to ordinary least squares to aid interpretation. The trendlines are computed within the provinces or for the whole country. Each trendline has the same color as the province and its districts or the color as used for Nepal in Figure 2. Inequality shows in the form of clear positive trends between the proportion of population coverage and wealth, especially if benefiting mostly the higher relative wealth.

We show only the figures for the most permissive metric that we consider: access within 60 minutes of driving. Figure 8 shows the situation as of May 2021, when only 69 laboratories were in operation, and as of November 2021, with 89. It includes all districts, including two districts in Bagmati province with full coverage and the highest relative wealth, Kathmandu and Bhaktapur. Figure 9 focuses on the less wealthy districts, omitting Kathmandu and Bhaktapur from the Bagmati province. In almost all cases we see that coverage grows alongside the growth of relative wealth.

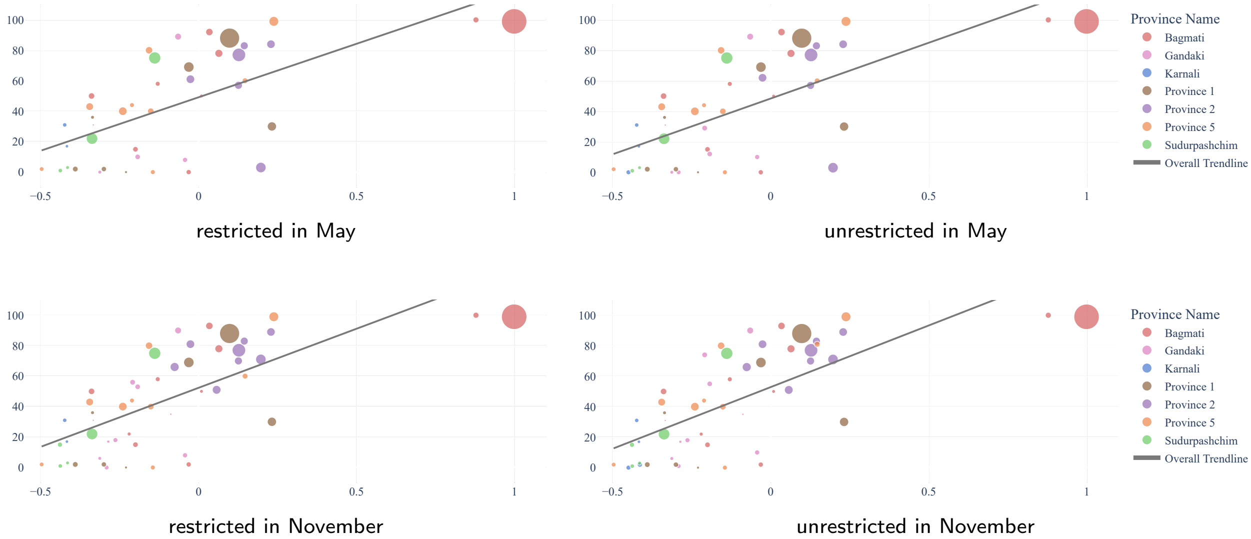



**Figure 8:** Accessibility per district to the closest laboratory within 60 minutes driving, restricted within the province of residence and not, at the beginning and the end of our period of study. The vertical axis shows the percentage of access while the horizontal axis places the district bubble in the relative wealth index range. The size of the bubble is proportional to the number of inhabitants and the color reflects the province. The overall trendline shows that access grows with wealth.

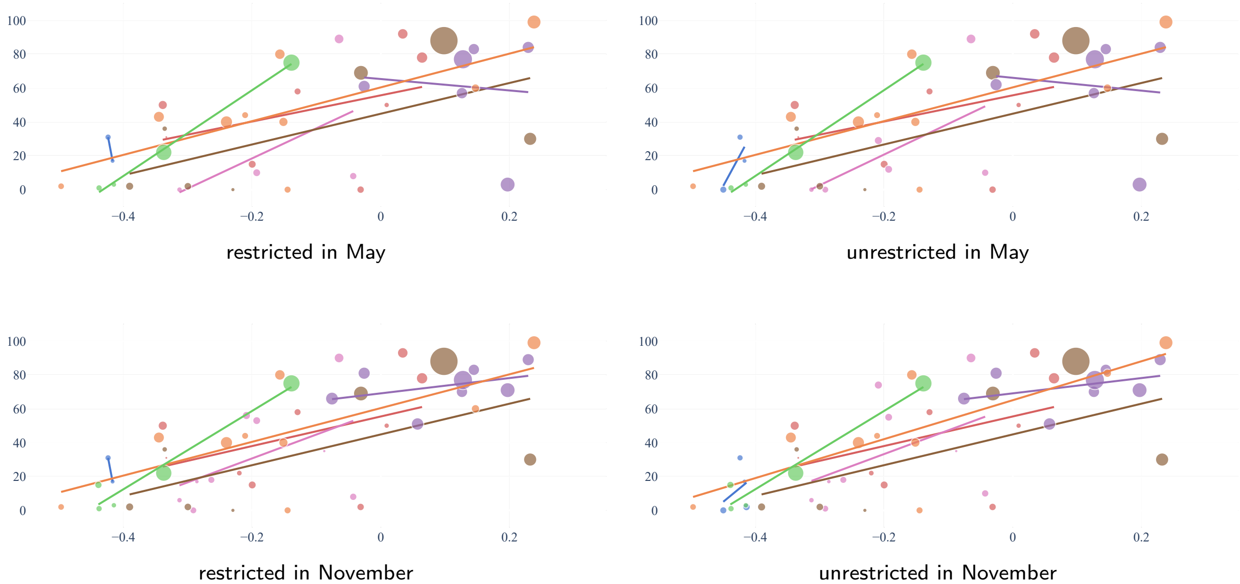



**Figure 9:** Accessibility per district to the closest laboratory within 60 minutes driving, without Kathmandu and Bhaktapur in the Bagmati province, under the same conditions as in Figure 8. The trendlines are now per province.

## 5. The potential of mathematical optimization

The Joint External Evaluation (JEE) exercise conducted in Nepal in late 2022 identified operations research as one of the priority actions for the laboratory pillar, see World Health Organization (2023). In order to illustrate the potential offered by mathematical optimization, a fundamental tool of operations research, we describe an optimization exercise using data from HealthSites.io as described in Saameli, Kalubi, Herringer, Sutton and de Roodenbeke (2018). This

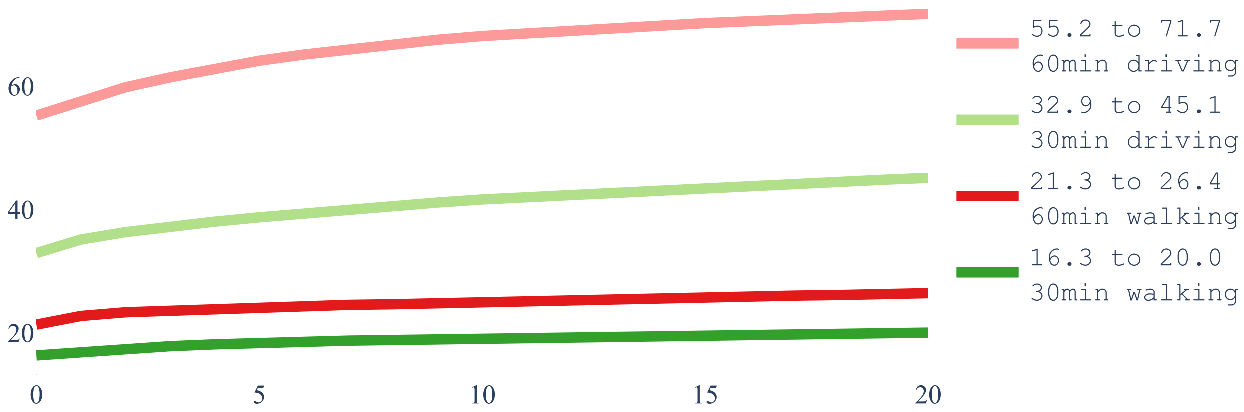



**Figure 10:** Pareto frontiers with the highest attainable coverage by optimal selection of 20 health centers to install as laboratories in addition to those in May 2021, selected from the 1682 health centers listed in Nepal by HealthSites.io plus the 20 actually used.

data lists 1 682 health centers in Nepal that we take as possible laboratory locations. We do not imply that these are realistic choices, but we want to illustrate the potential of mathematical optimization. An actual use of it would require careful identification of the candidate locations. We would have preferred using the apparently richer list of health centers used by Cao et al. (2021) but despite the description given in that paper, we could not find the data. That may explain why we observe lower accessibility as reported there. The difference may also lie in the metric used, but since the aforementioned paper does not offer the code used, we cannot compare.

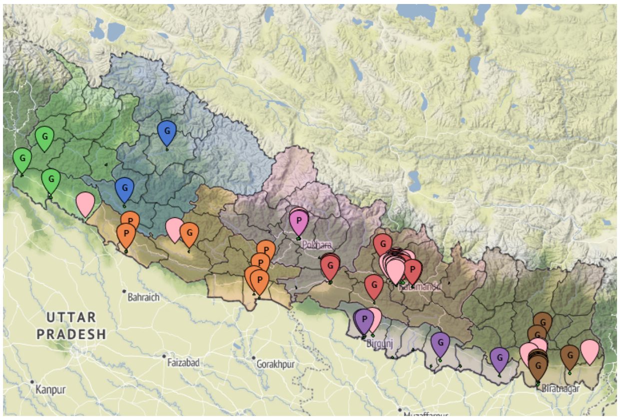
### 5.1. What if the 20 additional laboratories were chosen to optimize coverage?

We now use the optimization model presented in 3.2 and show in Figure 10 what could be attained if the 20 additional laboratories opened after May 2021 would have been selected optimally from all the potential laboratory locations listed by HealthSites.io plus the 20 ones that were actually opened. Since this section is illustrative of possibilities and no longer describes the situation in Nepal, we abandon the ‘same province’ rule. Redoing the analysis with the rule is straightforward, and we refer to Analytics for a Better World (2023) where our code and data are freely available.

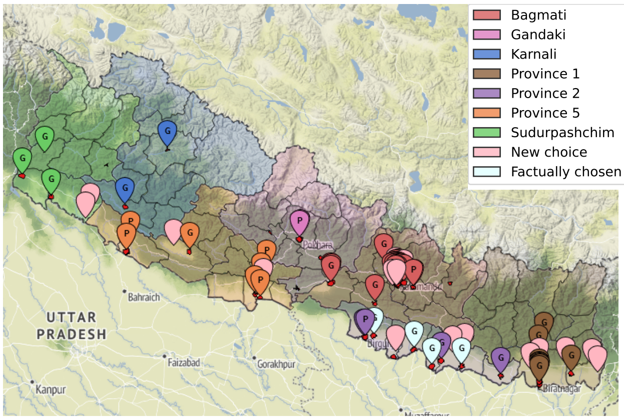
The four curves in Figure 10 are Pareto frontiers. They tell a different story than in Figure 3, which depicts the evolution in coverage for each additional laboratory, shown at the moment of its opening to the public. The horizontal axis of Figure 3 is a timeline while that on Figure 11 is a budget line. Each of the curves shows in Figure 10 the highest attainable coverage for the corresponding accessibility metric with $1, 2, 3, \ldots, 20$ additional laboratories. The end solutions, each obtained with 20 optimally chosen locations, are depicted in Figure 11. This figure shows the four different optimal solutions, one per metric, with 20 additions identifying the laboratories that coincidentally where also opened in Nepal and those that are new. Each subfigure also depicts the isochrones of the corresponding metric. Furthermore, the legends of the four subfigures compare the coverage obtained by the corresponding solution (the highest attainable within the metric and a budget of 20) with the factual coverage within that metric as of November 2021. This is the potential offered by mathematical optimization.

### 5.2. Expansion

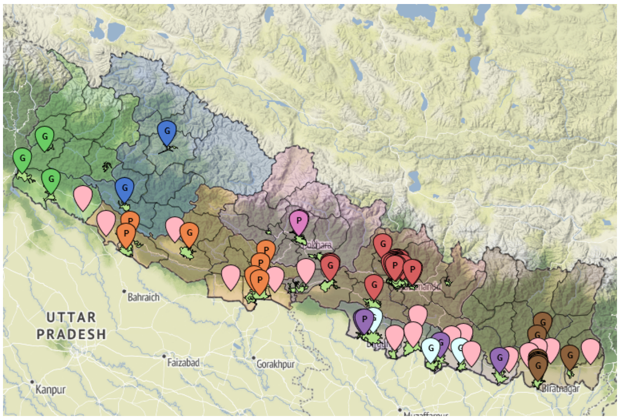
Suppose that we select the solution that maximizes accessibility for one hour of driving, on the bottom right of Figure 11, as the best one to implement. This entails two decisions: the budget, 20, and the metric, within one hour of motorized traveling time. To deploy this solution, we need to open each of the 20 laboratories. One could then implement the sequence of 20 laboratory openings that at each step maximize the gain in coverage. That can be done with a simple greedy selection from the pool of 20 optimal locations. We obtain a situation that evolves over time as described in Figure 2, but instead for the laboratories selected by optimization. After opening the last in the sequence, the coverage is the same as in the Pareto curve of the metric of choice, the one-hour driving, at the budget value of 20.



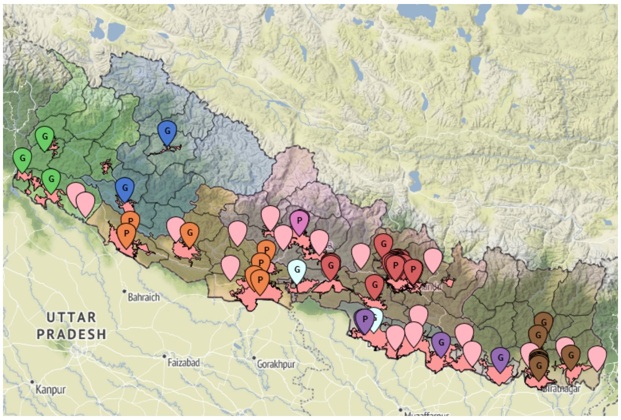

30 minutes walking: from 16.8% factual to 20.0% optimized




60 minutes walking: from 22.2% factual to 26.4% optimized




30 minutes driving: from 35.1% factual to 45.1% optimized




60 minutes driving: from 61.4% factual to 71.7% optimized

**Figure 11:** The optimal solutions with a budget for 20 laboratories in addition to the 69 in operation in May 2021 for each of the four different metrics considered, compared to the actual selection made in Nepal, when considering access regardless of province of residence. The solutions drawn correspond to Figure 10 and the coverage is compared to the values in the factual solution as in Figure 4. The pins of the locations selected in each case are colored to reflect if they match a location used in the factual solution implemented in Nepal as of November 2021 or are chosen from the new potential locations.

### *5.2.1. What are the limits?*

One additional question is: what is the highest attainable coverage with an unlimited budget, and how many new facilities does it require to be reached? That question is answered by the Pareto frontiers depicted in Figure 12. Two things are worth noticing:

1. in all cases just 375 out of the 1 682 potential locations suffice to achieve the highest attainable coverage.
2. these values, which being optimal do not change even if we open all 1 682 locations as laboratories, come quite short of the values reported by Cao et al. (2021). As mentioned, this can be due to not having access to the same list of health centers and/or to a different implementation of accessibility metrics.

In any case, the discrepancies observed when comparing to Cao et al. (2021) stress the value of both the data quality and the methodology adopted.

## 6. Optimizing with consideration for relative wealth

We will refer to the districts as 'left' and 'right' districts according to their positions on the scatterplots.

| Situations | 30min walking | 60min walking | 30min driving | 60min driving | left | right |
|---|---|---|---|---|---|---|
| Figure 4 | 16.8 | 22.2 | 35.1 | 61.4 | 35.2 | 85.3 |
| Allow 0 | 17.4 | 23.6 | 39.9 | 66.3 | 50.4 | 80.2 |
| Allow 1 | 18.0 | 25.0 | 41.9 | 68.4 | 50.4 | 84.2 |
| Allow 2 | 18.5 | 25.5 | 42.5 | 69.7 | 50.1 | 86.9 |
| Allow 3 | 18.9 | 25.6 | 43.1 | 70.5 | 49.6 | 88.8 |
| Allow 4 | 19.2 | 25.8 | 43.7 | 71.2 | 49.1 | 90.5 |
| Allow 5 | 19.4 | 25.9 | 44.0 | 71.7 | 48.6 | 91.9 |
| Allow 6 | 19.5 | 26.0 | 44.3 | 71.7 | 48.6 | 91.9 |
| Allow 7 | 19.6 | 26.1 | 44.6 | 71.7 | 48.6 | 91.9 |
| Allow 8 | 19.7 | 26.2 | 44.8 | 71.7 | 48.6 | 91.9 |
| Allow 9 | 19.8 | 26.2 | 44.9 | 71.7 | 48.6 | 91.9 |
| Allow 10 | 19.8 | 26.3 | 45.1 | 71.7 | 48.6 | 91.9 |
| Allow 11 | 19.9 | 26.3 | 45.1 | 71.7 | 48.6 | 91.9 |
| Allow 12 | 19.9 | 26.4 | 45.1 | 71.7 | 48.6 | 91.9 |
| Allow 13 | 20.0 | 26.4 | 45.1 | 71.7 | 48.6 | 91.9 |
| Figure 10 | 20.0 | 26.4 | 45.1 | 71.7 | 48.6 | 91.9 |

**Table 4**
Comparison of the national coverage across the four different metrics plus a subdivision in left and right districts for the one-hour driving metric for the solutions obtained from the initial 69 laboratories as in May 2021 complemented with 20 laboratories chosen in sixteen different ways: factually as implemented in November, Figure 4, allowing the given number of laboratories to open in right districts and the solution that maximizes headcounts with access as in Figure 10.

So far, our optimization considered each individual as equal. In light of the differences in relative wealth, one may consider promoting accessibility for those who are relatively less wealthy. One way of doing so is to safeguard a minimum of laboratories to be opened in districts where we want to promote accessibility. This can be done as follows:

1. define a subset $K \subseteq J$ of the potential laboratory locations as those in the districts that we want to promote.
2. decide on a minimum number $k$ of choices to be taken from $K$ in the optimal solution.
3. add the constraint $\sum_{j \in K} x_j \geq k$ to the optimization model.

In our experiments, we took as $K$ the subset of potential locations from left districts and we defined $k$ as the optimization budget $p$ minus a number of locations allowed on districts in right districts. The case $k = 0$ is the case when all laboratories (20 in our case) are allowed in any district and corresponds to optimizing purely for headcounts, as in Figure 10.

We summarize in Table 4 the outcomes of the situation as of November 2021 compared with the possible outcomes from the optimization. Since allowing for any number above 13 repeated the solution obtained when allowing all, the table omits those rows.

Notice that at a national scale, each situation depicted in Table 4 improves on the status quo from November for all accessibility metrics considered. Our metric of choice, one-hour driving, attains its highest value when allowing only 5 laboratories to open in right districts. The last two columns show the percentage of the population with access within a one-hour drive, considering only the population in left or right districts. Note that 46.7% of the Nepalese reside in left districts while 53.3% reside in right districts. The best situation for left districts is when the whole budget is reserved, allowing 0 laboratories in right districts. As soon as 5 laboratories are allowed in right districts we obtain the solution in the bottom right of Figure 11. Figure 13 shows the effect of controlling the number of laboratories to open in left or right districts. We see clearly the effects on the accessibility across the relative wealth index scale.

## 7. Discussion

Our results clearly show that the motorized mode delivers better geographical accessibility than the walking mode (see Figure 3 where the proportion of the population served by the driving mode is several orders of magnitude larger than that by the walking mode).

Unrestricted access to testing regardless of province borders returned a larger number of districts with access to at least 1 laboratory whether for travel time or distance thresholds. Also common across thresholds is the fact that valley districts in the south of Nepal have greater access to laboratories than districts in the mountainous areas of the north.

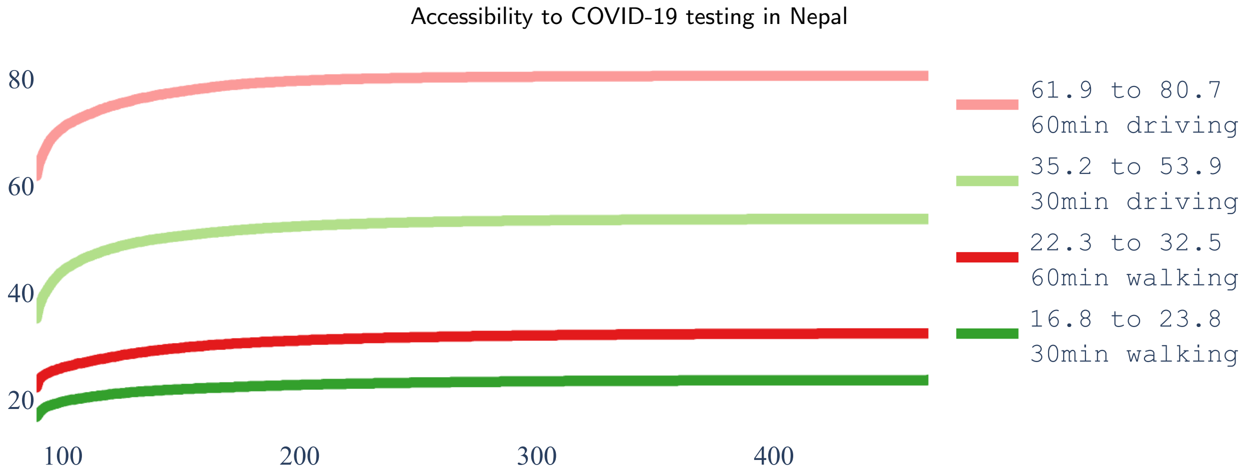



**Figure 12:** Highest attainable coverage by optimal selection with unbounded budget selected from the 1 682 health centers listed in Nepal by HealthSites.io.

We have seen the widespread presence of heterogeneity in accessibility across districts, with wealthier districts having better accessibility to laboratories (Figures 8 and 9). These figures also show that smaller districts, in terms of population size, tend to have worse accessibility (although no formal analysis was conducted).

Optimizing the location of the 20 laboratories that opened in the period May 2021 to November 2021 would have led to improvements in accessibility across all thresholds. We also illustrated that a simple way to benefit the population with lower relative wealth does not seem to compromise the nationwide results. Our results could support government decisions on the possible location of mobile laboratories for COVID-19 testing and determining their service area; we did not however assess critical considerations for the effective functioning of these mobile facilities such as their deployment readiness or location-specific capacities such as availability of health personnel to address sampling demands.

We note that Nepal recently conducted its first Joint External Evaluation (JEE) exercise, World Health Organization (2023). The JEE report identifies several laboratory-specific strategic capacities for further development that demand subsequent operational and more granular planning. Our findings aim to contribute to this latter ask by supporting the Ministry of Health and Population (MoHP) decisions on the possible location of mobile laboratories for testing to service areas of greater need or vulnerability. We believe that wider recommendations could also be derived from our work. Mainly, the significance of conducting a needs assessment as done by the MoHP and WHO in late 2020 triggered this research. We would go further to suggest the deployment of mechanisms to capture this information regularly during outbreak response to populate panel analyses of capacities and capabilities. Our work did not assess such critical considerations for the effective readiness of testing laboratories such as the availability and skillset of laboratory personnel to address sampling and testing demands. Such an exhaustive exercise would have required panel data on the capacities and capabilities of each operating laboratory. The only data on such critical operational variables was available in the form of a cross-sectional survey conducted by the MoHP and WHO in November 2020 to all operating laboratories at the time.

## 8. Limitations

Ours constitutes the first and most basic approach to the assessment of healthcare accessibility, screening in our case, by geographical coverage of the population. Aiming at the strategic decision of where to install testing facilities we did not intend to explore the many nuances, e.g. disease severity and comorbidities, and vaccination coverage, which may explain the observed testing behavior and demand as captured by our data. This is a different and more complex work than the one presented here, well beyond the limited time and data available to us during the emergency.

Our models of coverage are not demand-driven as we did not consider any variability in the number of tests required by the population as COVID-19 spread across the country. Furthermore, we did not consider any population characteristic that might inform demand heterogeneity, e.g. some laboratories charging for testing while others offer a gratuitous service.

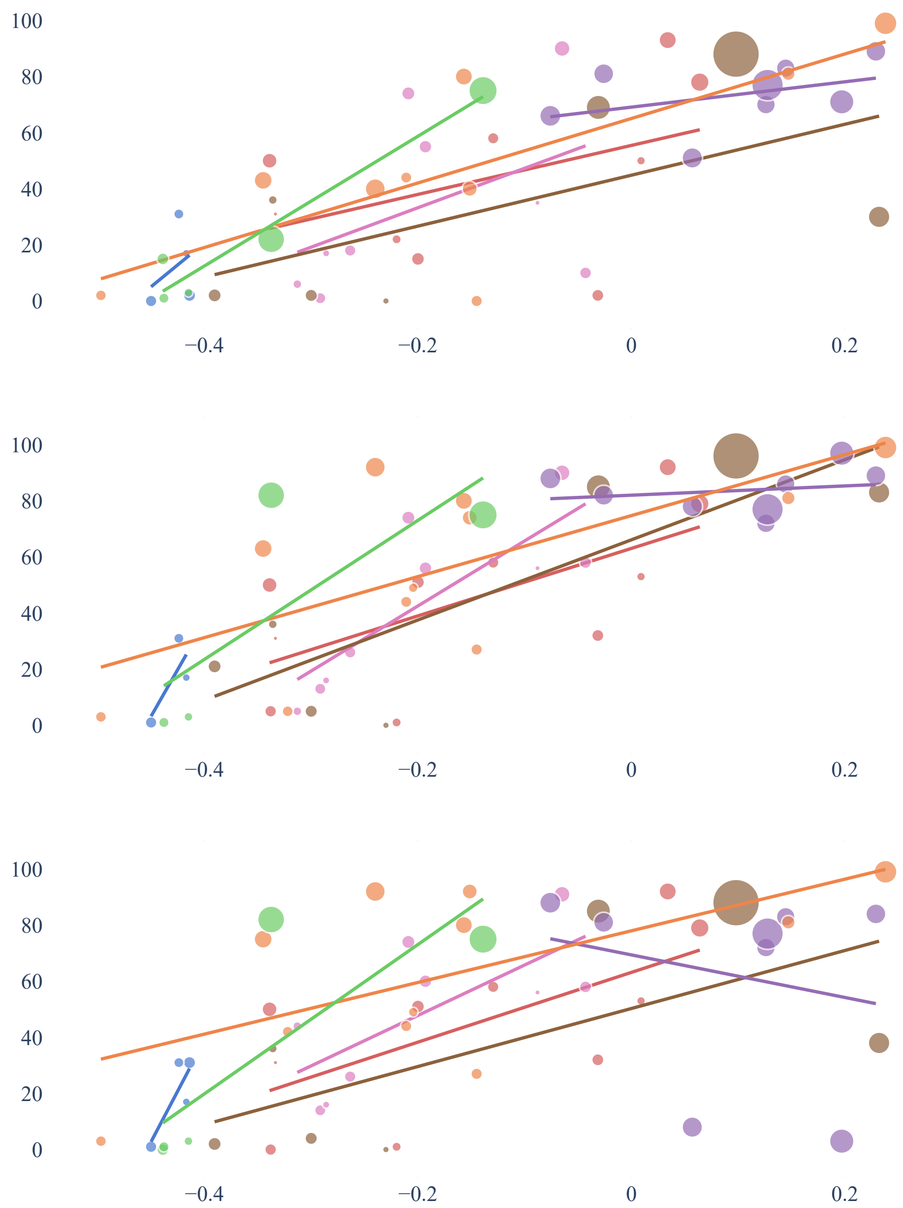



**Figure 13:** Accessibility per district to the closest laboratory within 60 minutes driving, as of November 2021 (above), and when optimizing taking relative wealth index into account by allowing only 5 of the 20 new labs to be in right districts (center) and none (below).

We used relative wealth for each district as a proxy indicator of the availability of transportation to reach the laboratories to inform equitable access. This presents several limitations: i) we could not validate how reliable wealth is of transportation accessibility due to the lack of data on, for example, car ownership and public transport availability; ii) we only present a crude association between relative wealth and accessibility without adjusting for potential confounders such as the proportion of elderly people who are less likely to have access to a car in general; and iii) we lacked granularity of heterogeneities within the districts that could show different access, for example, between rural and urban areas or indeed between genders. We based our calculation of coverage on access to at least one laboratory within the established isochrones; yet this does not account for the fact that the closest laboratory might not have the capacity to handle more samples if demand is heightened. In such situations, pairing laboratories to others nearby might still provide equitable access to testing services as reported by Bakker et al. (2024).

# 9. Data provenance

## 9.1. Data sources

This section describes the data used and the data considered to use in this work.

### *9.1.1. Google Geocoding API (June 2021)*

Google Maps Platform

Geocoding is the process of converting addresses (like "1600 Amphitheatre Parkway, Mountain View, CA") into geographic coordinates (like latitude 37.423021 and longitude -122.083739), which you can use to place markers on a map or position the map. The Geocoding API provides a direct way to access these services via an HTTP request. We used this service via a python API to geocode the location of COVID-19 test laboratories in Nepal, which was then manually verified by our team.

The use of open-source services geocoding such as those based on OSM proved insufficient for our needs due to lack of accuracy in Nepal.

### *9.1.2. MapBox Isochrone API (July 2021)*

MapBox Isochrone API

The Mapbox Isochrone API computes areas that are reachable within a specified amount of time from a location and returns the reachable regions as contours of polygons or lines that you can display on a map. and allow to identify the households that meet the corresponding accessibility thresholds with the need to compute exact individual travel times.

### *9.1.3. Digital elevation models (April 2024)*

Stamen Terrain

Terrain maps, featuring hill shading, used as background tiles on the map figures. The shading serves as a digital elevation model to show the challenging geography of Nepal.

### *9.1.4. Beneficiaries/Population from World Pop (June 2021)*

Population Counts

Estimated total number of people per grid-cell. The dataset is available to download in Geotiff and ASCII XYZ format at a resolution of 30 arc (approximately 1km at the equator). The projection is Geographic Coordinate System, WGS84. The units are the number of people per pixel with country totals adjusted to match the corresponding official United Nations population estimates that have been prepared by the Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat (2019 Revision of World Population Prospects). The mapping approach is Random Forest-based asymmetric redistribution.

### *9.1.5. Potential locations for laboratories (June 2021)*

HealthSites.io

Repository as described in Saameli et al. (2018). This data lists 1 682 health centers in Nepal.

### *9.1.6. Administrative Boundaries (June 2021)*

Nepal Administrative Boundaries

Nepal administrative level 0-2 and district (unnumbered) boundaries.

### *9.1.7. COVID-19 Laboratories (June 2021)*

All Province Profile

Detailed description of the laboratory facilities established in the seven provinces in response to the COVID-19 pandemic is given in PDF Files.

CoVid19-Dashboard

The COVID-19 Dashboard of Ministry of Health, Nepal also publishes Situation Reports daily to give information on COVID-19 Cases, Deaths, Test Positivity Rate.

#### *9.1.8. Relative Wealth Index (June 2021)*

Nepal Relative Wealth Index Data from Humanitarian Data Exchange

Researchers at the University of California - Berkeley and Facebook developed micro-estimates of wealth and poverty that cover the populated surface of all 135 low and middle-income countries (LMICs) at 2.4km resolution. The estimates are built by applying machine learning algorithms to vast and heterogeneous data from satellites, mobile phone networks, topographic maps, as well as aggregated and de-identified connectivity data from Facebook. They train and calibrate the estimates using nationally representative household survey 20 data from 56 LMICs, then validate their accuracy using four independent sources of household survey data from 18 countries. They also provide confidence intervals for each micro-estimate to facilitate responsible downstream use.

### 9.2. Dead ends

The previous subsections describe the data sources used. Before selecting those, many others were considered, in particular for road networks. We started with an extraction of roads from OpenStreetMap data made by WFP following UNSDI-T standards. The data is updated in near-real time from OSM servers and includes all the latest updates. Since this dataset does not include streets and pathways that have been published on a separate dataset (streets and pathways) we merged those. This dataset enables the computation of realistic travel distances with scalable algorithms such as contraction hierarchies. However, travel times lack realistic speed estimates, and we were forced to use MapBox instead. The travel times produced by MapBox were validated by local experts and considered accurate.

## 10. Description of individual contributions

Each author contributed as described below during the whole project:

- Parvathy Krishnan Krishnakumari: conceptualization, data collection, data verification, analysis, application of methodology, conclusions, manuscript production.
- Hannah Bakker: conceptualization, data collection, data verification, analysis, methodology validation, manuscript review.
- Nadia Lahrichi: conceptualization, data verification, analysis, methodology validation, manuscript review.
- Fannie L. Côté: conceptualization, data verification, analysis, methodology validation, manuscript review.
- Joaquim Gromicho: conceptualization, data verification, analysis, application of methodology, conclusions, manuscript production.
- Arunkumar Govindakarnavar: project lead, conceptualization, manuscript review.
- Priya Jha: domain expertise, data validation, manuscript review.
- Saugat Shrestha: domain expertise, data validation, manuscript review.
- Rashmi Mulmi: domain expertise, data validation, manuscript review.
- Nirajan Bhusal: domain expertise, data validation, manuscript review.
- Deepesh Stapith: domain expertise, data validation, manuscript review.
- Runa Jha: domain expertise, data validation, manuscript review.
- Lilee Shrestha: domain expertise, data validation, manuscript review.
- Reuben Samuel: local and regional domain expertise, data validation, manuscript review.
- Dhamari Naidoo: local and regional domain expertise, data validation, manuscript review.
- Victor del Rio Vilas: project lead, conceptualization, manuscript review.

## Disclaimer

This work represents the personal opinion of the authors and not that of the World Health Organization.

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