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Mobile Logistics Hubs (MLHs) Prepositioning for Emergency Preparedness and Response

WFP
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Government of Nepal
Ministry of Home Affairs

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Foreword

Nepal's vulnerability to natural disasters, including earthquakes, landslides, flooding, droughts and most recently wind storms provides a compelling case for research and investment in emergency preparedness. In the last five years alone, United Nations World Food Programme has supported the government of Nepal in four emergency operations to support over 2.7M affected people. The earthquakes that struck Nepal in 2015 affected 31 districts, resulted in the deaths of 9,000 people, and cost an estimated USD 7 billion to the economy. Monsoon floods in 2014 and 2017 are estimated to have affected almost 2 million people; approximately 65,000 houses were destroyed, and 460,000 people displaced.

A Humanitarian Staging Area (HSA) was opened only a month prior to the 2015 earthquakes. The HSA facility funded by UK Aid and operated jointly by WFP and Nepal's Ministry of Home Affairs, is estimated to have saved 21 days in response time, enabling life saving supplies to reach the affected population quicker. The facility managed 38,375 metric tonnes of cargo for 164 organizations within a period of 11 months.

Building on preparedness work undertaken in 2013-2015 which established the HSA and applying lessons learnt from the earthquake response, a second-phase emergency preparedness project *"Augmentation of National and Local-Level Emergency Logistics Preparedness in Nepal,"* was initiated. This is a three-year project (2017-2020) supported by UK Aid, the Australian Government, and WFP-Nepal. The concept of prepositioning Mobile Logistics Hubs (MLHs), is to enable a quicker and effective emergency response in remote regions of the country. Together, the Humanitarian Staging Area in Kathmandu, the Forward Logistics Bases in the Terai and mid-hill regions of each province, and Mobile Logistics Hubs prepositioned close to areas at risk of disasters, form a hub-spoke supply chain system ensuring a more cost and time effective response during disasters to save lives and reduce the disaster impact.

Given the results of the research study, a dissemination and consensus building workshop will be planned for all relevant stakeholders including but not limited to donors, provincial government representatives, representatives from the Ministry of Home Affairs, security forces, and the members of the logistics cluster. The research study will be presented to gather feedback and solicit operational knowledge and local expertise of various stakeholders to identify the sites where MLHs can be prepositioned with collaboration of the local government.

Furthermore, this research aims to contribute to the humanitarian logistics preparedness strategy and literature, by developing a methodology that can be used to determine hub locations in other countries at risk of disasters.

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Abstract

Disaster response is very challenging. Logistics hubs play a critical role in improving overall responsiveness and effectiveness of the humanitarian supply chain; determining their optimal location contributes to an effective supply chain. The April 2015 Nepal earthquake highlighted the importance of having in-country mobile logistics hubs, yet the process of determining their ideal sites has been based on a subjective decision process. This study aims to determine the best placements for Mobile Logistics Hubs (MLHs) across the country by considering the disaster scenarios of earthquakes, landslides, and floods. This study employs the concepts of human development, disaster risk, and transportation accessibility to reflect Nepal's socioeconomic, geo-climatic, and topographical features. The study uses an amalgamation of quantitative and qualitative approaches to determine an optimal solution for Nepal which has limited resources for investment in disaster preparedness.
It uses a modified version of the maximal covering location problem to determine the number and location of MLHs and fuzzy factor rating system and fuzzy multi-attribute group decision-making approach to identify the order of establishment of the MLHs.

Keywords: Humanitarian logistics, Integer programming, Facility location problem, Maximum coverage, Emergency preparedness, Mobile logistics hub (MLH)

Study objective

The objective of this study is to the determine the optimal number and spatial location of Mobile Logistics Hubs (MLHs) to be placed in different parts of Nepal for enhancing preparedness to multiple disasters considering disaster scenarios of earthquake, landslide and flood. The study also identifies the order of establishment of the selected MLHs.

Abbreviations

ADPC	Asian disaster preparedness centre
CDVI	Composite disaster vulnerability index
DOLIDAR	Department of Local Infrastructure Development and Agricultural Roads
FLB	Forward logistics base
GIS	Geographical information system
HDI	Human development index
ICIMOD	International Centre for Integrated Mountain Development
MCLP	Maximal covering location problem
SCLP	Set covering location problem
MLH	Mobile logistics hub
MSU	Mobile storage unit
POD	Point of distribution
UNHRD	United Nations Humanitarian Response Depot

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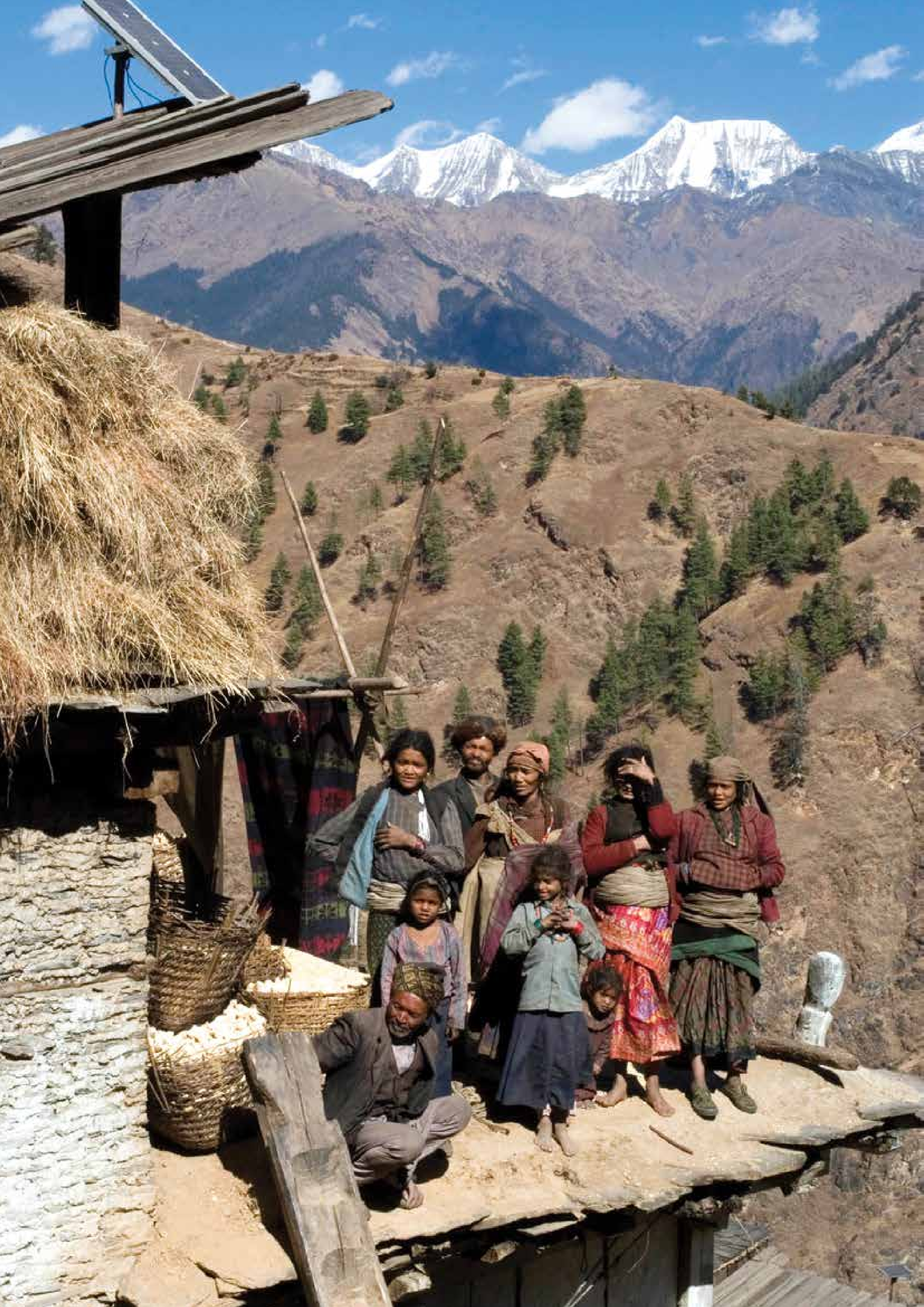


1. Introduction

The number of people affected by humanitarian crises has greatly increased over the past decade, leading to unprecedented challenges for the humanitarian system. With the increasing impact of disasters, an effective response strategy becomes obligatory. Disasters can be triggered by natural, political, or economic events, their occurrence can destroy the very infrastructure of a country affecting the social, economic, and physical supports of the society. Unlike slow-onset disasters, the sudden ones give responders a very short time to react and prevent further damage. Considering the urgency, uncertainty, and complexity associated with managing disasters, enhancements in logistics and supply chain management directly affects the ability of humanitarian organisations to respond and improve overall effectiveness of the response. Disaster response can be extraordinarily challenging in a developing country due to insufficient resources in the immediate aftermath, poor governance, weak infrastructure, damages to infrastructure and a general lack of information, including a response plan and knowledge of the socioeconomic circumstances in affected areas. Hence, being prepared for disasters is critical to the success of humanitarian response efforts.

The concept of *planning* or *preparedness* encompasses outlining a set of actions to be taken in the event of a disaster. It is essential to anticipate problems that may occur in the supply chain at an early stage. Put simply, appropriate preparedness is critical for a timely, competent, efficient, and cost-effective emergency response (McGuire, 2001). Preparedness may include developing a disaster response framework, pre-positioning emergency relief and rescue materials, as well as training and educating the public. Implemented properly, a combination of these strategies can save many lives and minimise suffering. Among the various aspects of preparedness, we focus on pre-positioning relief and rescue materials since doing so significantly reduces the time needed to take action following a disaster.

Location selection plays a vital role in ensuring the success of a pre-positioning strategy. Placing facilities far from potential demand points might lead to longer delivery times, but being closer to demand nodes exposes them to disasters. Striking the proper balance is key. Facility location models in humanitarian logistics determine the most suitable sites for pre-positioning inventories by considering several stochastic as well as deterministic factors; these include cost, response time, location safety, demand coverage, and distance. Facility location models are classified according to their purpose such as evacuation operations, stock pre-positioning, or joint stock pre-positioning and relief distribution. The term *facility* is used interchangeably with *warehouse* in this study. A warehouse can be viewed as permanent or temporary, based on the length of the operation. The placement of permanent warehouses is often a long-term strategic decision meant to anticipate disasters since these facilities involve major capital investments and have far-reaching effects. Permanent warehouses include those of the United Nations Humanitarian Response Depot (UNHRD), a global network of strategically located sites in Panama, the United Arab Emirates, Italy, Spain, Malaysia, and Ghana. In contrast, temporary warehouses are set up only after a disaster strikes, usually in the form of mobile storage units or using existing homes as makeshift.

Nepal is a landlocked country in South Asia. The country is prone to various types of natural calamities due to its fragile geophysical structure, which is characterized by very high peaks, complex geology, active tectonic processes, unplanned settlements, variable climatic conditions, and weak economic and political circumstances (ADPC 2010). Every year numerous floods, landslides, fires, epidemics, avalanches and other natural and humanmade crises causes loss of hundreds of lives and billions of rupees' worth of property. The earthquakes of 1934, 1980, 1988, and 2015 and the floods of 1993 and 2008 were particularly devastating; countless human lives were lost, physical property ruined, and the development process of the entire country adversely affected. Currently with 25.2% of the population living under the national poverty line (ADB 2016), responding to a disaster without prior preparation can severely impact emergency response.

In this study, we focus determining the location of Mobile logistics hubs (MLH's) with the aim of increasing efficiency and effectiveness of emergency response operations. A MLH is defined as a place pre-designated for storing emergency logistics and emergency telecommunication equipment. The main aim of establishing an MLH is to preposition logistics equipments including Mobile Storage Units (MSU's) to establish a relief logistics operation center at a remote location near to the disaster-affected area(s). The objective is to quickly establish an operation center to function as a humanitarian platform for management of disaster relief items with the availability of communication systems. MLHs are to be strategically located in different parts of Nepal with the ability to cover districts vulnerable to sudden-onset disasters like flood, landslide, and earthquake. In this study, MLHs and PODs are considered at district level granularity due to the input data being at the same level.

Table 1 shows the statistics for different disasters in Nepal and the number of lives lost between the years 1900 and 2016, illustrating that floods, landslides, and earthquakes are the most common types of sudden-onset crises and claim the highest number of lives.

Many studies have addressed the importance of preparedness and the need for pre-positioned warehouses in humanitarian relief logistics. Although research on facility location problem is abundant in the domain of humanitarian operations (Balcik and Beamon 2008; Dessouky, Murali, and Ordóñez 2009; Rawls and Turnquist 2010; Campbell and Jones 2011;

Table 1: Types of disasters, number of occurrences and deaths per type (1900-2016) (CRED, 2016)

S.N	Type of Disaster	Number of Occurrences	Number of Deaths
1	Earthquake	8	18,905
2	Flood	44	6,768
3	Epidemic	20	4,568
4	Landslide	25	1,883
5	Extreme temperature	7	217
6	Storm	7	180
7	Wildfire	2	88
8	Drought	6	0

Roh et al. 2015), reviews of existing studies show a general lack of attention to country-specific situations. It is rare to come across investigations that focus on location problems and consider multiple disaster vulnerabilities, the availability of basic data, factors unique to the nation being examined, and which contain reflections on the current state of disaster preparedness in the country. Hence, our main contribution lies in addressing this gap in literature for facility location problem using real data from Nepal, with the aim of reducing disaster vulnerability by increasing preparedness. Our overall objective is to determine the number of MLHs required and their optimal locations where emergency relief materials can be pre-positioned across Nepal. We use a deterministic model with a single objective. We consider three factors unique to Nepal: (1) transportation accessibility, (2) level of development and (3) disaster vulnerability. These three factors are introduced as constraints in the mathematical model which are among the factors that will affect the choice of MLH location. Further, qualitative factors were also selected to determine the order of establishment of selected MLHs which include: (1) availability of open spaces for establishing MLH, (2) proximity to the airport, (3) the level of safety in the selected site, (4) the availability of utility infrastructure in prospective locations, (5) availability of labor, (6) proximity to disaster vulnerable districts, (7) support from local government, and (8) proximity to the armed police force disaster management.

2. Literature review

One of the most important aspects of humanitarian operations is to decide where to locate facilities such as MLHs, evacuation centres, and medical centres. Use of these facilities during response operations is known to improve the humanitarian supply chain's overall responsiveness and effectiveness. These strategic decisions are crucial determinants of the humanitarian supply chain's success or failure. While there are many variants to modelling location problems, Caunhye et al. (2012) divided the literature into two specific categories: facility location and relief distribution. Facility location models can be further subdivided into pure location models (e.g. Jia et al. 2007), inventory models (e.g. Campbell and Jones 2011) and models that combine both location and inventory decisions (e.g. McCoy and Brandeau 2011; Jahre et al. 2016). Boonmee et al. (2017) classified location models based on the data modelling types and problem types: deterministic facility location problems, stochastic facility problems, dynamic facility problems, and robust facility problems. The deterministic location models can be further classified into the minisum facility location problem, the covering problem, and the minimax facility location problem. In this study, we model our problem as a covering problem under the category of pure location model. Covering models are the most widely used location models for formulating emergency facility location problems (Jia et al. 2007).

A covering problem can be further categorised as a maximal covering location problem (MCLP) or a set covering location problem (SCLP). *Coverage*, a notion that is central to facility location models, indicates whether a demand location is within a pre-specified radius (measured by distance, travel time, cost or another metric) of the nearest facility. The source of demand is considered 'covered' if it is located within a specified response distance or time from a facility. The SCLP, first introduced by Hakimi (1965), seeks to minimise the number of facilities among a finite set of candidate sites such that all demand sources are covered. In disaster relief, this would mean that a potential demand point must be within a specified target response time of a facility in the relief network. On the contrary, the MCLP maximises the total demand covered within a maximal service distance, which is subjected to a limited number of facilities or resource constraints. Therefore, a maximal covering type model is more suitable for designing relief chain networks.

The P-median problem attempts to minimise the sum of the distances (i.e. average distances) between PODs and their nearest facilities. Although the MCLP and P-median problems address similar problem categories, the aim of the P-median problem is to minimise the total demand-weighted distance between each demand node and nearest facility. Put simply, this means pinpointing the locations of P-facilities in a network such that the total distance is minimised. However, Lee and Yang (2009) concluded that the P-median problem approach does not optimise demand coverage or site locations because in this approach, distance and time parameters can outweigh demand values, resulting in locations that are outliers. The MCLP approach avoids this by changing the objective from minimising travel distance to serving the greatest possible number of people. Furthermore, coverage models are known to be best for 'worst case scenarios' because the goal is to ensure the best possible response, even for the most remote PODs in the network.

We provide a brief overview of the studies that use the MCLP to choose locations. Church and ReVelle first introduced the MCLP in 1974. Subsequent developments of it were led by Chung (1986); Megiddo, Zemel, and Hakimi (1983); and Daskin, Hogan, and ReVelle (1988). Many researchers such as Basdemir (2004), Jia et al. (2007), Balcik and Beamon (2008), Murali et al. (2012), Santos et al. (2013), Abounacer et al. (2014), and Chanta and Sangsawang (2012) have used the MCLP to choose locations. Only few have actual case studies using multiple disasters. Jia et al. (2007) and Murali et al. (2012) use epidemics, Balcik and Beamon (2008) use worldwide disasters caused by earthquakes, while Santos et al. (2013) and Chanta and Sangsawang (2012) use floods to illustrate their cases.

Often, the objective of choice in a humanitarian operation is to maximise demand satisfaction or minimise response time (e.g. Balcik and Beamon 2008; Mete and Zabinsky 2010; Salmeron and Apte 2010; Duran et al. 2011; Bozorgi-Amiri et al. 2013; Barzinpour and Esmaeili 2014; Rennemo et al. 2014; and Jahre et al. 2016). Many studies focus on maximising demand coverage while maximising responsiveness, or minimising response time. Another aspect of the location problem is their multi-objective nature. Many studies model the location problem by considering its multi-objective nature (Tseng et al. 2007; Barzinpour and Esmaeili 2014, Sahebhamnia et al. 2017, Bastian et al. 2016, and Babaei and Shahanaghi 2016). The objectives of concern are often cost and budget, response time, and demand satisfaction. Minimising cost is a critical consideration; considering multiple objectives is equally important.

While there are several approaches to modelling a location problem, the existing literature fails to account for the unique characteristics of country-level factors that affect location selection. Kunz and Reiner (2012) found an underrepresentation of empirical research in a literature review of 174 papers. A brief look at Nepal's budget revealed almost no funds allocated for disaster preparedness activities, except for awareness training till the year 2014 (MoF, 2014). A small portion of the budget was allocated for reconstruction and recovery after the April 2015 Nepal earthquake (MoF, 2015). Given the current situation, Nepal is severely under-prepared for future disasters. Owing to the primitive nature of disaster preparedness and the expanse of the population at risk, this study aimed to maximise the demand coverage.

Therefore, with the aim to account for gaps in the existing literature and the specific need of the country, we formulate our problem as a modified version of an MCLP, which is a synthesis of various extensions developed for the maximal covering model. We use three types of sudden-onset disasters: earthquakes, landslides, and floods to develop a hazard map in order to identify the affected area PODs. We use real data from such calamities to pinpoint PODs and vulnerability index which make this study one of a kind. Our formulation is unique with the inclusion of country level specific parameters: transportation accessibility, the level of development, and the disaster vulnerability. Our main objective is to provide preliminary location information for deciding on the number of MLHs and their locations. Thus, the selection of locations based on maximum coverage enables providing relief to maximum PODs, and hence maximizing coverage becomes more suitable as an objective rather than cost. We aim to contribute the literature on the MCLP by focusing on the applicability of this model in real life disaster preparedness activities, by considering multiple disasters and country-specific attributes.

3. Methodology

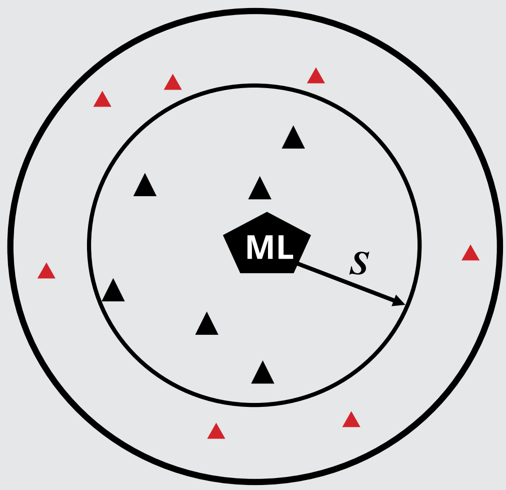
The methodology implemented in this study has been formulated to align with the overarching goal of establishing a sustainable and flexible 'logistics backbone' that can respond to the multiple disaster scenarios which face Nepal by establishing 4 MLHs in different parts of Nepal. The methodology amalgamates quantitative and qualitative approaches. Amalgamation of these approaches plays an important role in eliciting important knowledge and information. Especially in developing countries, its often difficult to obtain quantitative data. Data often exists in the form of the knowledge gained by experts in due process. Therefore, in this study we have adopted a method that extracts valuable knowledge from experts termed as decision-makers and convert it into numbers (quantitative values) to enable mathematical calculations. To do so, we have employed the concept of fuzzy set theory and linguistic variables. The methodology is presented in two sequential steps: in the first step we determine the optimal number and spatial location of MLHs, in the second step we determine the order of establishing the MLHs obtained from the first stage. The detailed description and implementation of the steps are explained in subsequent sections.

3.1 Determining the number and location of MLHs

We formulated our problem as a modified version of an MCLP. The MCLP maximizes the total demand covered within a maximal service distance, which is subjected to a limited number of facilities or resource constraints. This study considers the uncertainty of disaster occurrence using scenarios of floods, landslides, and earthquakes to determine vulnerable PODs. It also takes into account important factors such as the distance between the prospective locations and PODs, road accessibility and connectivity, and the sustainable operability of the MLHs in the selected locations. The model maximizes the coverage of PODs subject to a set of three constraints: (1) the transportation accessibility constraint, (2) the development constraint, and (3) the disaster safety constraint. We use road density, human development index (HDI), and composite disaster vulnerability index (CDVI) as the proxy to represent transportation accessibility, level of development and disaster safety. We set the threshold values for the three indices to maintain minimum standards for the selected MLH locations. The model includes the candidate points, which are the potential sites for MLHs, and the PODs that need to be covered.

We consider an emergency supply chain network $G = (N, A)$, where N is the set of nodes and A is the set of arcs. Here N is composed

Figure 1: Illustration of the concept of coverage



Where,
S = stipulated coverage distance within which facilities can cover PODs
▲ = PODs "covered" within the stipulated coverage distance
▲ = PODs "uncovered" within the stipulated coverage distance

of the set of mobile logistics hubs (MLHs), *M*, and points of distribution, *P*, i.e., N = M ∪ P. The aim here is to identify the number and spatial location of MLHs to cover PODs with the objective of maximizing POD coverage. Generally, when designing a humanitarian supply chain network, it is important to make sure that the established facilities can cover the demand areas within stipulated coverage distance. Therefore, this study has implemented the notion of coverage. Figure 1 shows an illustration of the concept of coverage. In Figure 1, the PODs located within the *S* distance termed as "coverage distance", which are highlighted in black are considered "covered" whereas the ones highlighted in red colour are considered "uncovered".

3.1.1 Formulation of the MCLP model

The MCLP has been formulated as a static, single-stage deterministic problem based on the following assumptions:

- All the MLHs are considered incapacitated.
- The locations of MLHs are assumed to be in district headquarters.
- All PODs have road access to and from the candidate MLH locations.
- The PODs are either fully covered or uncovered. There is no provision for partial coverage; the coverage follows binary requirements.

With reference to the original formulation proposed by Church and ReVelle (1974), followed by Basdemir (2004), for non-disaster scenarios, and the one proposed by Balcik and Beamon (2008) for disaster scenarios, we have adapted our model under additional constraints and variables according to Maharjan and Hanaoka (2017) to meet this study's requirements. The mathematical formulation is as follows:

$$\text{Maximise} \quad \sum y_i \qquad (1)$$

$$\text{S.T.} \quad \sum x_j \geq y_i \quad \forall i \in I, j \in J \qquad (2)$$

$$\sum x_j \leq P \qquad (3)$$

$$\sum T_j x_j \geq N_T \sum x_j \quad \forall j \in J \qquad (4)$$

$$\sum D_j x_j \geq N_D \sum x_j \quad \forall j \in J \qquad (7)$$

$$\sum V_j x_j \leq N_V \sum x_j \quad \forall j \in J \qquad (6)$$

$$x_j \in \{0,1\} \quad \forall j \in J \qquad (7)$$

$$y_i \in \{0,1\} \quad \forall i \in I \qquad (8)$$

Where,

I denotes the set of PODs

J denotes the set of MLHs

P = number of MLHs to locate

$$x_j = \begin{cases} 1 & \text{if a MLH is located at candidate site } j \in J \\ 0 & \text{if otherwise} \end{cases}$$

$$y_i = \begin{cases} 1 & \text{if a POD is covered within the coverage distance} \\ 0 & \text{if otherwise} \end{cases}$$

N_T = the minimum threshold value for transportation accessibility

N_D = the minimum threshold value for development index

N_V = the maximum threshold value for disaster vulnerability index

T_j = the transportation accessibility index value for candidate site *j*

D_j = the development index value for candidate site *j*

V_j = the disaster vulnerability index value for candidate site *j*

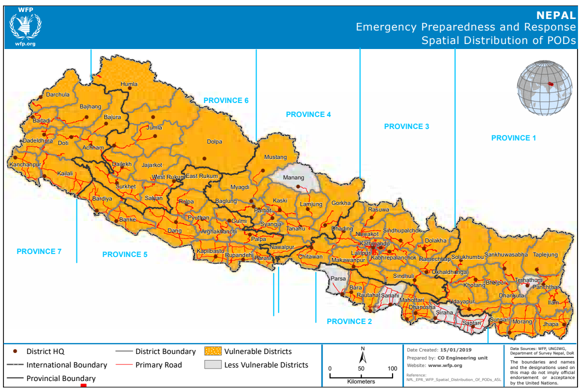
The objective function (1) maximises the total demand covered. Constraint (2) represents the coverage constraint. Based on coverage distance, each candidate MLH has a certain number of PODs it can cover; likewise, each POD has a set of candidate MLHs that can cover it. In other words, POD at node $i \in I$ will not be covered unless at least one MLH that covers node i is selected. The coverage distance determines the maximum distance within which a potential MLH can cover nearby PODs. The coverage distance also determines the maximum number of MLHs that can be established: the larger the coverage distance, the smaller the number of MLHs that are needed to fulfil all the PODs (and vice versa). Constraint (3) sets a limit on the total number of MLHs that can be opened. An increase in the number of MLHs causes costs to rise and simultaneously boosts the service level provided to the PODs. Constraints (4), (5), and (6) are the limiting constraints for transportation accessibility, level of development, and disaster safety associated with each POD. The constraints stipulate that the values of transportation accessibility and level of development should be greater than or equal to the required minimum threshold values for these indices and less than or equal to the maximum threshold values for disaster safety to be selected as MLH locations. These constraints help to establish minimum standards for choosing MLH locations.

3.1.2 Identification of PODs

A wide variety of sudden and slow-onset disasters strike Nepal every year. We have chosen three types of sudden-onset disasters (earthquakes, landslides, and floods) to determine the PODs. The consideration is based on the fact that these three kinds of calamities combined result in the highest frequency of occurrence among all types of natural disasters in Nepal and have resulted in significant fatalities. It is worth noting that the three types are not mutually exclusive.

The disaster scenarios were developed based on existing academic and non-academic studies. The earthquake scenario was generated using the maximum number of fatalities projected on the study conducted by Robinson et al. (2018). The study estimates relative seismic risk that relies on an ensemble of scenarios representing potential future earthquakes. The authors claim that this approach is particularly well-suited to

Figure 2: Spatial distribution of PODs



For enlarged map please see annex

countries like Nepal, where earthquake hazard is relatively poorly understood, information on earthquake recurrence intervals is limited, and earthquake hazard maps contain widely differing results. The landslide scenario was generated based on the 2010 *Nepal Hazard Risk Assessment report* (ADPC, 2010). This was the most recent countrywide study on landslide available for Nepal which estimates the annual probability of occurrence of potentially destructive landslide event by an appropriate combination of the triggering factors (mainly extreme precipitation and seismicity) and susceptibility factors (slope, lithology, and soil moisture). Weighted average district area percentage distribution for landslide was created by combining the district area percentage distribution for earthquake induced landslide and precipitation induced landslide. The flood scenario was generated based on study conducted by Dhonju et al. (2015) under ICIMOD using risk measure which is the product of vulnerability and hazard measures. The study uses three categories of data; historical disaster events, socio-economic and physiographic data for risk assessment for dynamic web mapping of vulnerability, hazard and risk.

To begin, we conducted risk assessment and developed a composite disaster vulnerability index (CDVI) using arithmetic mean of the normalized values of earthquake, landslide, and flood risks. The resulting districts were charted over the map of Nepal using Arc GIS 10.2.2 to identify the PODs, and pinpointed 70 districts as disaster-prone with the cut-off CDVI set at 0.2 based on mutual consensus of the study team.

Figure 2 shows the spatial distribution of PODs over the map of Nepal; The districts vulnerable to either or all of the three sudden onset disasters had been highlighted by orange yellow colour. The rest of the districts (non-coloured) are considered relatively safe from the sudden-onset natural disasters.

3.1.3 Identification of PODs to be covered by MLHs

Under the implementation strategy devised by WFP, for the augmentation of national and local-level emergency logistics preparedness in Nepal, eight forward logistics bases (FLB) are planned/proposed to be established in Banke, Kailali, Kaski, Kathmandu, Morang, Parsa, Rupandehi, and Surkhet districts with an estimated capacity of 2000 MT each. A FLB is a main staging area which forwards cargo to MLHs in the affected areas. However, the coverage provided by the planned/proposed FLBs are yet to be determined. Therefore, to avoid redundancy in demand coverage and ensuring equitable reachability of different logistical facilities, we firstly determine the PODs which can be covered by planned/proposed FLBs within the stipulated coverage distance. By removing the PODs covered by FLBs we obtain the PODs to be covered by MLHs.

To identify the PODs covered by FLBs, we implement the original formulation of MCLP without the additional constraints.

3.1.3.1 Problem definition

We consider an emergency supply chain network *G = (N, A),* where N is the set of nodes and A is the set of arcs. Here N is composed of the set of forward logistics bases, F, and points of distribution, *P*, i.e., $N = F \cup P$. The aim here is to identify which FLBs cover which PODs with the objective of maximizing POD coverage.

3.1.3.2 Model assumptions

The MCLP has been formulated as a static, single-stage deterministic problem based on the following assumptions:

- FLBs are considered incapacitated.
- The location of FLBs are known.
- The distances between the PODs and FLBs are known.
- The PODs are either fully covered or uncovered. There is no provision for partial coverage.

3.1.3.3 Mathematical model

Forward logistics base (FLB) model presented below has been derived from the original formulation proposed by Church and ReVelle (1974).

$$\text{Maximize} \quad \sum y_i \qquad (1)$$

$$\text{S.T.} \quad \sum x_j \geq y_i \quad \forall\, i \in I \;\; j \in J \qquad (2)$$

$$\sum x_j \leq P \quad \forall j \in J \qquad (3)$$

$$x_j \in \{0,1\} \quad \forall j \in J \qquad (7)$$

$$y_i \in \{0,1\} \quad \forall i \in I \qquad (8)$$

Where,

I = the set of PODs

J = the set of FLBs

S = the distance beyond which a POD is considered uncovered (the value of S can be chosen differently for different FLBs if desired)

d_{ij} = the shortest distance from node i to node j

$C_i = \{j \in J \mid d_{ij} \leq S\}$

$$y_i = \begin{cases} 1 & \text{if POD i is covered by FLB j within the stipulated coverage distance} \\ 0 & \text{if not} \end{cases}$$

$$x_j = \begin{cases} 1 & \text{if FLB j is selected} \\ 0 & \text{if not} \end{cases}$$

P = the number of FLBs

C_i is the set of FLBs eligible to provide "cover" to PODs *i*. A POD is "covered" when the closest FLB to that node is at a distance less than or equal to S. A POD is "uncovered" when the closed FLB to that node is at a distance greater than *S*.

The objective function (1) maximizes the total PODs covered by FLBs. Constraint (2) represents the coverage constraint. Based on coverage distance, each candidate FLBs has a certain number of demand nodes it can cover; likewise, each POD has a set of

FLBs that can cover it. In other words, POD at node $i \in I$ will not be covered unless at least one FLB that covers node i is selected. The coverage distance determines the maximum distance within which a FLB can cover nearby PODs. The coverage distance also determines the maximum number of FLBs that can be established: the larger the coverage distance, the smaller the number of FLBs that are needed to fulfil the POD demand (and vice versa). Constraint (3) shows the maximum number of FLBs that can be sited: An increase in the number of FLB causes costs to rise and simultaneously boosts the service level provided to the PODs. Therefore, this constraint sets a limit on the total number of FLBs that can be opened. We consider the transport of relief items via roads, such that the distances between the FLBs and PODs are the actual distances on Nepal's existing road networks. Constraints (7) and (8) depict the nature of decision variables.

3.1.3.4 Model parameters

A total of 70 PODs are identified as the vulnerable nodes that would require delivery of emergency relief in case of disasters. Eight FLBs are located in Nepalgunj in Banke district, Dhangadi in Kailali district, Pokhara in Kaski district, Kathmandu, Biratnagar in Morang district, Birgunj in Parsa district, Bhairahawa in Rupandehi district, and Birendranagar in Surkhet district. A coverage distance of 150km is considered for FLBs located in Banke, Kailali, Morang, Parsa, Rupandehi, and Kathmandu and a coverage distance of 100km is considered for FLBs located in inner hill/terai and middle mountains, namely Surkhet and Pokhara. A coverage distance of 150 km is selected for Terai region considering a maximum vehicular speed of 30 km/hr and 100 km for mountainous region considering a maximum vehicular speed of 20 km /hr and an average working hour of 8 hours per day. The coverage distance selection is pertinent to a flatbed truck with a maximum loading capacity

Table 2: Demand distribution showing the PODs covered by FLBs within the stipulated coverage distances

District Name	Kathmandu	Rupandehi	Parsa	Kaski	Morang	Banke	Surkhet	Kailali
FLB Location	Kathmandu	Siddharthanagar	Birgunj	Pokhara	Biratnagar	Nepalgunj	Birendranagar	Dhangadi
Coverage distance	150km	150km	150km	100km	150km	150km	100km	150km
List of PODs covered	Bara	Arghakhanchi	Bara	Baglung	Dhankuta	Banke	Banke	Bardiya
	Bhaktapur	Dang	Bhaktapur	Kaski	Jhapa	Bardiya	Surkhet	Kailali
	Chitwan	Kapilbastu	Chitwan	Myagdi	Kanchanpur	Dang	Dailekh	
	Dhading	Nawalpur	Kathmandu	Nawalpur	Morang	Surkhet		
	Dolakha	Palpa	Lalitpur	Syangja	Sunsari			
	Gorkha	Parasi	Makwanpur	Tanahu	Udayapur			
	Kathmandu	Parbat	Rautahat					
	Kavrepalanchok	Rupandehi						
	Lalitpur							
	Makwanpur							
	Nuwakot							
	Rasuwa							
	Sindhupalchok							
	Tanahu							

of 12 tons, loading time of 1.5 hours, and unloading time of 1.5 hours. The objective here is to identify the districts which can be covered by the established/proposed FLBs.

3.1.3.5 Results

The result of the model shows that a total of 37 districts shown in Table 2 can be covered by the established/proposed FLBs within the stipulated coverage distances of 100km and 150km. Figure 3 shows the spatial location of FLBs and the PODs covered by it over the map of Nepal. From Table 1 it can also be observed that some districts like Bara, Bhaktapur, Banke, Kathmandu, Lalitpur, Makwanpur (to name a few) can be covered by more than one FLB. This is an important finding which allows the decision-maker to decide on multiple/different allocation strategies. Planned appropriately, multiple allocation strategy can help in building resilience of humanitarian supply chain. Another important observation is that FLBs in different locations have different number of PODs that they can cover. This provides insights for planning capacities of the FLBs. Varying the capacities allocated to different FLBs based on their POD coverage can facilitate in minimizing establishment costs and inventory related costs.

The remaining 33 PODs located outside the coverage distance of the FLBs (presented in Table 6 in Appendix) are therefore identified as the PODs to be covered by MLHs.

3.1.4 Selection of candidate MLHs

Nepal is administratively divided into seven provinces that are further divided into 77 districts. Government of Nepal along with other national and international non-governmental organizations have existing and planned warehouses of different forms and sizes in 18 districts located in Baitadi, Banke, Dang, Dhanusa, Doti, Kailali, Kanchanpur, Kaski, Kathmandu, Lamjung, Makwanpur, Morang, Panchthar, Parsa, Rupandehi, Sunsari, Surkhet and Udayapur districts of Nepal. Therefore, in this study, we consider rest of the 59 districts (presented in Table 7 in appendix) as candidate MLH locations. The PODs and candidate MLH locations are allowed to overlap because the disaster safety indicated by CDVI value outweighs the advantage of putting MLHs in potentially safe locations far from disaster-prone areas, with the drawback of placing MLHs in disaster-prone districts (i.e. PODs). This allows the MLHs to be located both in disaster-prone and potentially safer districts.

3.1.5 Selection of constraints

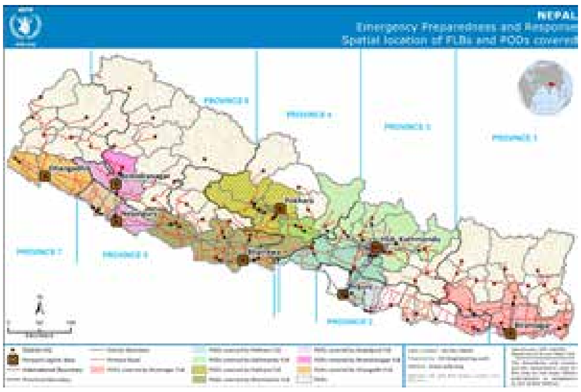
Several factors affect choosing locations in real life. An appropriate site must be accessible to and from the demand node so that it has a lower probability of being affected by disasters, and must be sufficiently developed to keep the facility running. Therefore, we use the notion of transportation accessibility, level of development, and disaster vulnerability as constraints to formulate the model. These three indices exemplify this study. The main idea behind using these constraints is to ensure that the determined MLH locations can meet the incoming demand within a short response distance, while also guaranteeing the safety and sustainability of the chosen location. This, in turn, ensures the safety of the emergency relief items stored in the MLHs. Next, we explain the details of constraint selection.

The notion of transportation accessibility, represents the accessibility constraint and is a proxy used to signify the ease of access to PODs from the sites where MLHs might be placed. We derived the index values from road density data (DOLIDAR, 2016), which show kilometres of existing roads (per 100 square kilometre of land) for each POD. In this model, higher index values indicate better locations for MLH sites. The road density values associated with each MLH is presented in Table 7 in Appendix.

The notion of disaster vulnerability represents the vulnerability constraint and is a proxy used to reflect each POD's safety level. Here the term safety means that districts are less vulnerable to disasters and are thus safer locations for placing MLHs. Each district is susceptible to different types of disasters and therefore exposed to varying degrees of risk; thus, each district has a unique value in the vulnerability index. The candidate MLHs are assigned the CDVI which was also used to identify PODs. While some PODs have high CDVI values, others are ostensibly risk-free. The PODs predisposed to lower CDVI values means that they are potentially safer compared to those with higher values. Thus, the model seeks lower values of CDVI. The CDVI values associated with each MLH is presented in Table 7 in Appendix.

The notion of level of development represents the development constraint and is a proxy used to illustrate and compare each candidate MLH's level of development. We derived the data for this index from human development index (HDI) (NPC 2014), which is essentially a measure of life expectancy, education, and per capita income indicators. A district with a higher value of HDI (aggregated geometric mean) is more developed; it has easier and better access to work-force as

Figure 3: Spatial location of FLBs and PODs covered



For enlarged map please see annex

well as resources for building and managing MLHs, ultimately ensuring the sustainability of the selected locations. A higher level of development is also important for selected sites' operational security. The HDI values associated with each MLH is presented in Table 7 in Appendix.

We determined distance by using a combination of web-based application called the shortest distance calculator provided by Nepal's Department of Roads (Department of Roads, 2019) and strategic road network GIS file(Department of Roads, 2013). This calculator is unique to Nepal; it has an updated database of road networks within the country. Due to Nepal's extremely diverse geography, poor infrastructure and weak economic circumstances, overall road network and density are low; only 43% of the population has access to all-weather roads (ADB 2016). Therefore, to figure out the most accurate scenario, it is important to measure the exact driving distance (instead of Euclidean distance). We could not use other methods (such as Google maps) due to the lack of a proper database.

3.1.6 Model Implementation and results

The MLH model was implemented for a network of 33 PODs (presented in Table 6 in Appendix)and 59 candidate MLHs (presented in Table 7 in Appendix) with a coverage distance of 100 km. A coverage distance of 100 km is selected considering a maximum vehicular speed of 20 km/hr in the mountainous region and an average working hour of 8 hours per day. The coverage distance selection is pertinent to a flatbed truck with a maximum loading capacity of 12 tons, loading time of 1.5 hours, and unloading time of 1.5 hours. A threshold value of 30 km/100 sq. km land for road density, 0.37 for level of development, and 0.55 for disaster vulnerability is selected for the model implementation. We consider the transport of relief items via roads, such that the distances between candidate points and PODs are the actual distances on Nepal's existing road networks.

The model was coded using Lingo 17.0 Optimization modelling software. All the experiments were run on a personal computer with an Intel (R) Core (TM) i5-7500 CPU (3.40 GHz) and 16 GB of RAM. All the test problems were computed in under 5 minutes.

Figure 4 shows the percentage of PODs covered by varying number of MLHs. We can observe 12 as the maximum number of MLHs which can be opened under given circumstances. An increase in the number of MLHs did not lead to increase in coverage of PODs. This could be because of two reasons: (1) some of the candidate MLHs although satisfy the distance constraint, do not have desired level of transportation accessibility, level of development, and disaster vulnerability; and (2) some of the candidate MLHs although satisfy transportation accessibility, level of development, and disaster vulnerability constraints lies beyond the desired coverage distance.

The 12 MLHs are located in Achham, Bhojpur, Dadeldhura, Gulmi, Illam, Khotang, Mahottari, Okhaldhunga, Pyuthan, Ramechhap, Salyan, and Tanahu districts which can cover a total of 21 PODs located in Achham, Bajura, Bhojpur, Baitadi, Dadeldhura, Doti, Gulmi, Illam, Panchthar, Khotang, Dhanusa, Mahottari, Sindhuli, Okhaldhunga, Solukhumbu, Pyuthan, Rolpa, Ramechhap, Rukum west, Salyan, and Lamjung districts within a 100 km coverage distance. Table 3 shows the allocation of PODs to MLHs. We can observe that a maximum of 3 PODs and a minimum of 1 POD can be served by a MLH. Figure 5 shows the spatial location of 12 MLHs and the PODs served by MLHs over the map of Nepal.

3.2 Identifying the order of establishment of MLHs

Identification of the order of establishment of MLHs plays a crucial role in enabling appropriate allocation/utilization of available

Figure 4: Percentage of PODs covered by MLHs

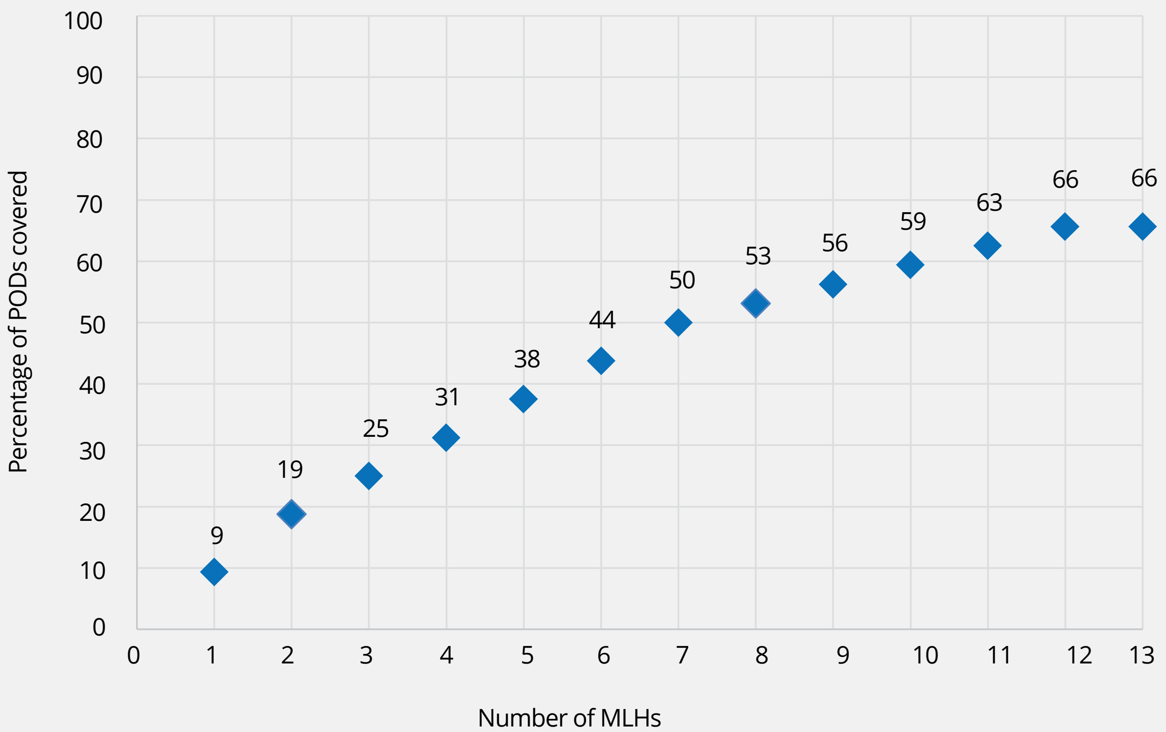
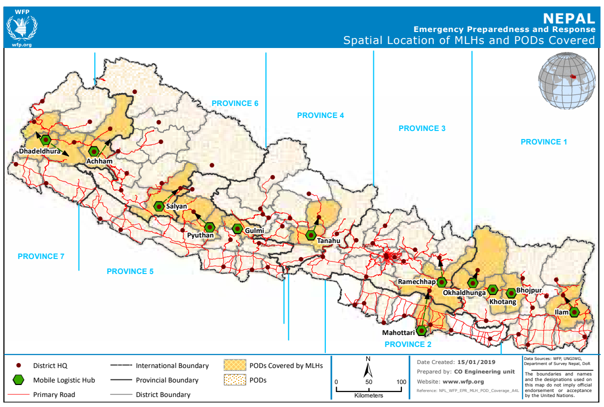


Table 3: Allocation of PODs to open MLHs

S.N.	MLH locations	PODs covered		
1	Achham	Achham	Bajura	
2	Bhojpur	Bhojpur		
3	Dadheldhura	Baitadi	Dadeldhura	Doti
4	Gulmi	Gulmi		
5	Ilam	Illam	Panchthar	
6	Khotang	Khotang		
7	Mahottari	Dhanusa	Mahottari	Sindhuli
8	Okhaldhunga	Okhaldhunga	Solukhumbu	
9	Pyuthan	Pyuthan	Rolpa	
10	Ramechhap	Ramechhap		
11	Salyan	Rukum West	Salyan	
12	Tanahu	Lamjung		

resources while also ensuring sustainable operability of the established MLHs. Under the given circumstance, WFP has resources enough to establish four MLHs among the 12 identified by the MCLP model. Therefore, we have implemented the methodology developed by Maharjan and Hanaoka (2019, In press) to determine the order of establishment of the 12 MLHs. The methodology involves two steps, in the first step the importance weight of attributes is computed using a modified form of fuzzy factor rating system and in the second step the order of establishment is determined using a fuzzy multi-attribute group decision-making approach. These two steps are explained in detail below.

Figure 5: Spatial location of MLHs and PODs covered



For enlarged map please see annex

3.2.1 Computing the importance weight of attributes to evaluate MLHs

The main purpose of this stage is to determine the importance weight of the subjective attributes used in evaluating MLH location alternatives. In this study, we adapted the “fuzzy factor rating system under group decision making condition” developed by Maharjan and Hanaoka (2018) to calculate the importance weights of subjective attributes. The fuzzy factor rating system under group decision-making uses fuzzy logic to account for the inherent vagueness and uncertainty associated with decision-making during disaster response. Fuzzy logic allows impersonating ambiguous and uncertain linguistic knowledge and offers a robust framework for model designers dealing with systems that contain high uncertainty (Aguilar-Lasserre et al., 2009). Trapezoidal fuzzy numbers are the most widely used form of fuzzy numbers because they can be handled arithmetically and interpreted intuitively (Chou et al., 2008). Hence, the linguistic terms assessing scarcely quantifiable variables are represented by trapezoidal fuzzy numbers in this study. The modified mechanism is composed of six sequential steps, explained hereunder.

Step 1: Selection of attributes.
Several attributes play an important role in determining the order of establishment of MLHs. These factors are pertinent to the needs of specific country/region. In this study, the term “attribute” is used to refer to subjective attributes only. The attributes are selected based on a variety of criteria, including the socio-economic situation of the country, the geo-climatic situation, a literature survey, a review of lessons learned from the reports of past disasters, and expert opinion.

Table 4 shows the list of eight attributes used in this study. The attributes were selected to ensure the sound utility, operational sustainability of the established MLHs, and ease of coordination with other stakeholders.

Table 4: List of attributes

S.N.	Attributes	Attribute ID
1	Availability of Open spaces for establishing MLH	C1
2	Proximity to airport	C2
3	Level of safety in the selected site	C3
4	Availability of utility infrastructure	C4
5	Availability of labor	C5
6	Proximity to disaster vulnerable districts	C6
7	Support from local government	C7
8	Proximity to armed police force disaster management	C8

Step 2: Selection of decision-makers.

Under the GDM scenario, multiple decision-makers can be chosen. The choice of decision-makers varies from case-to-case and country by country. A committee of decision-makers can be formed based on their overall role in the disaster management activity.

We have selected 11 decision-makers belonging to different governmental and non-governmental organizations for evaluating the 8 attributes selected in this study.

Step 3: Determining the degree of importance of decision-makers.

The next step is to determine if decision-makers are homogeneous or heterogeneous. If the degree of the importance of decision-makers is equal, then the group of decision-makers is deemed a homogeneous group; otherwise, the group is deemed heterogeneous.

In a committee of k decision-makers (Dt, t = 1, 2, ...,k) responsible for assessing m alternatives (A_i, i=1, 2, ..., m), under each of the n attributes (C_j, j=1, 2, ..., n), as well as importance of attributes, the degree of importance of the decision-makers is I_t, t = 1, 2,..., k, where
$I_t \in [0,1]$ and $\sum_{t=1}^{k} I_t = 1$. If $I_1 = I_2 = \ldots = I_k = \frac{1}{k}$,
the group of decision-makers is called a homogeneous group; otherwise, the group is called a heterogeneous group.

Within the scope of this study, all the 11 decision-makers have been considered homogeneous.

Step 4: Collecting decision opinions and computing the aggregated fuzzy rating of individual attributes.

The decision opinions of decision-makers were obtained using an online questionnaire interview. The questionnaire uses the linguistic variables outlined in Table 8 in Appendix to enable decision-makers to assess the importance of the attributes. The linguistic variables are used for rating the attributes in the manner employed by Liang and Wang (1991), Liang (1999), Yong (2006) and Chou et al. (2008). Table 5 shows decision-opinion of decision-makers using linguistic variables for eight attributes.

Subsequently, to compute the aggregated fuzzy rating of the individual attributes, let $\widetilde{W}_{jt} = (a_{jt}, b_{jt}, c_{jt}, d_{jt})$, j = 1, 2, ..., n; t = 1, 2, ..., k, be the linguistic rating given to attributes $C_1, C_2, \ldots, C_n$ by decision-maker D_t. The aggregated fuzzy rating, $\widetilde{W}_j = (a_j, b_j, c_j, d_j)$, of attribute C_j assessed
by the committee of k decision-makers is defined as

$$\widetilde{W}_j = (I_1 \otimes \widetilde{W}_{j1}) \oplus (I_2 \otimes \widetilde{W}_{j2}) \oplus \ldots \oplus (I_k \otimes \widetilde{W}_{jk}), \quad (9)$$

where $a_j = \sum_{t=1}^{k} I_t a_{jt}$, $b_j = \sum_{t=1}^{k} I_t b_{jt}$, $c_j = \sum_{t=1}^{k} I_t c_{jt}$, $d_j = \sum_{t=1}^{k} I_t d_{jt}$.

Table 6 shows the aggregate fuzzy ratings obtained for eight attributes using equation (9).

Step 5: Computing the importance weight of attributes.

To compute the importance weight of attributes, we defuzzify the fuzzy rating of the individual attributes, compute the normalized weights, and construct the weight vector. To defuzzify the rating of the fuzzy attributes, the signed distance is adopted.

Table 5: Decision-opinion of decision-makers for eight attributes

Attri-butes	List of decision-makers										
	D_1	D_2	D_3	D_4	D_5	D_6	D_7	D_8	D_9	D_{10}	D_{11}
C_1	High	Very High	Very High	High	Low	High	Very High	High	Very high	Medium	High
C_2	High	Low	High	Low	Very low	High	Low	High	Medium	High	Very High
C_3	High	Medium	High	Medium	Low	High	Medium	High	High	High	High
C_4	Medium	High	Very High	Medium	Medium	High	Medium	Very High	High	Very high	Very High
C_5	Medium	High	High	Medium	Medium	High	Medium	Medium	Very high	Very high	High
C_6	High	Very High	Very High	Medium	High	High	High	Very High	Low	Very high	Very High
C_7	Medium	High	Very High	High	Low	High	Very High	Very High	Medium	High	High
C_8	Medium	Medium	High	High	Low	Medium	Medium	High	Medium	Medium	Medium

The defuzzification of $\tilde{w}_j$, denoted as d($\tilde{w}_j$), is therefore given by

$$d(\widetilde{W}_j) = \frac{1}{k}(a_j + b_j + c_j + d_j) \tag{10}$$

The crisp value of the normalized weight for attributes C_j, denoted by W_j, is given by

$$W_j = \frac{d(\widetilde{W}_j)}{\sum_{j=1}^{n} d(\widetilde{W}_j)}, \tag{11}$$

where $\sum_{j=1}^{n} W_j = 1$. The weight vector W = $[W_1, W_2, \dots, W_n]$ is therefore formed.

The defuzzified aggregated fuzzy rating and the crisp value of the normalized weight of the attributes C_j obtained is presented in Table 6. Based on the decision opinion of 11 decision makers, availability of open spaces for establishing MLH was found to be the most important attribute with the highest normalized weight, this is then followed by proximity to disaster vulnerable districts and support from local government with equal importance, availability of utility infrastructure, level of safety in the selected site and availability labor with equal importance followed by proximity to armed police force disaster management. Proximity to the airport was identified to be the least important of the eight attributes.

3.2.2 Determining the order of establishment of MLHs

Using the subjective knowledge of the decision-makers, to facilitate the establishment of 4 MLHs, this stage determines the sequence of establishing 12 MLHs by evaluating each MLH

Table 6: The importance weight of attributes

Attributes	Aggregated fuzzy rating	Defuzzified aggregated fuzzy rating	Normalized weight of attributes
C1	(5.38, 7.94, 7.94, 9.56)	7.70	0.15
C2	(2.88, 5.25, 5.25, 7.75)	5.28	0.10
C3	(3.75, 6.13, 6.13, 9.06)	6.27	0.12
C4	(4.63, 7.38, 7.38, 9.25)	7.16	0.13
C5	(3.88, 6.56, 6.56, 9.00)	6.50	0.12
C6	(4.88, 7.56, 7.56, 9.13)	7.28	0.14
C7	(4.88, 7.50, 7.50, 9.31)	7.30	0.14
C8	(3.00, 5.63, 5.63, 8.56)	5.70	0.11

location against the eight selected attributes. To do so, fuzzy multi-attribute group decision-making developed by Maharjan and Hanaoka (In Press) is used. The following summarizes the main steps involved in this fuzzy multi-attribute group decision-making method.

Step 1: Obtain the decision-opinions of decision-makers to assess alternatives with respect to individual attributes, and obtain aggregated fuzzy ratings.

To assess the fuzzy ratings of location alternatives with respect to individual attributes, we obtain the decision-opinions of decision-makers using the linguistic variables outlined in Table 9, and pool them together to obtain the aggregated fuzzy ratings.
An interview questionnaire was used for obtaining rating of alternatives.

Let $\tilde{x}_{ijt} = (o_{ijt}, p_{ijt}, q_{ijt}, r_{ijt})$, *i = 1, 2, ... , m; j = 1, 2, ... , n; t = 1, 2, ... , k,* be the linguistic suitability rating assigned to alternatives for attributes by decision-maker. The aggregated fuzzy rating of alternative A_i for attribute C_i assessed by the committee of *k* decision-makers is defined as

$$\tilde{x}_{ij} = (I_1 \otimes \tilde{x}_{ij1}) \oplus (I_2 \otimes \tilde{x}_{ij2}) \oplus \ldots \oplus (I_k \otimes \tilde{x}_{ijk}), \quad (12)$$

This can subsequently be represented and computed as:

$\tilde{x}_{ij} = (o_{ij}, p_{ij}, q_{ij}, r_{ij})$, *i = 1, 2, ... , m, j = 1, 2, ... , n*

where $o_{ij} = \sum_{t=1}^{k} I_t o_{ijt}$, $p_{ij} = \sum_{t=1}^{k} I_t p_{ijt}$
$q_{ij} = \sum_{t=1}^{k} I_t q_{ijt}$, $r_{ij} = \sum_{t=1}^{k} I_t r_{ijt}$.

Table 11 in appendix presents the decision-makers' evaluation for each alternative.

Step 2: Construct a fuzzy rating matrix.

In the second step we construct fuzzy rating matrix $\tilde{M}$ based on fuzzy ratings, and express concisely in the matrix format

$$\tilde{M} = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{bmatrix}$$

where, $\tilde{x}_{ij}, \forall i,j$ is the aggregated fuzzy rating of alternative A_j with respect to attribute C_j. Table 8 presents the fuzzy rating matrix.

Step 3: Derive the total fuzzy scores for individual alternatives by multiplying the fuzzy rating matrix by its respective weight vectors.

We obtain the total fuzzy score vector by multiplying the fuzzy rating matrix $\tilde{M}$ by the corresponding weight vector *W, i.e.,*

$$\tilde{F} = \tilde{M} \otimes W^T = \begin{bmatrix} \tilde{x}_{11} & \tilde{x}_{12} & \cdots & \tilde{x}_{1n} \\ \tilde{x}_{21} & \tilde{x}_{22} & \cdots & \tilde{x}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & \tilde{x}_{m2} & \cdots & \tilde{x}_{mn} \end{bmatrix} \otimes \begin{bmatrix} W_1 \\ W_2 \\ \vdots \\ W_n \end{bmatrix} =$$

$$\begin{bmatrix} \tilde{x}_{11} \otimes W_1 \oplus \tilde{x}_{12} \otimes W_2 \oplus \cdots \oplus \tilde{x}_{1n} \otimes W_n \\ \tilde{x}_{21} \otimes W_1 \oplus \tilde{x}_{22} \otimes W_2 \oplus \cdots \oplus \tilde{x}_{2n} \otimes W_n \\ \vdots \\ \tilde{x}_{m1} \otimes W_1 \oplus \tilde{x}_{m2} \otimes W_2 \oplus \cdots \oplus \tilde{x}_{mn} \otimes W_n \end{bmatrix} =$$

$$\begin{bmatrix} \tilde{f}_1 \\ \tilde{f}_1 \\ \vdots \\ \tilde{f}_m \end{bmatrix} = [\tilde{f}_i]_{m*1}, \quad (13)$$

where $\tilde{f}_i = (s_i, t_i, u_i, v_i)$.

Table 7 presents the fuzzy ratings matrix which has been constructed using the aggregated ratings in Tables 7 and 11 in appendix.

Step 4: Compute the crisp values using a defuzzification method.

To compute the crisp values we defuzzify the fuzzy scores $\tilde{f}_1, \tilde{f}_2, \ldots, \tilde{f}_m$ by using signed distance method. The following defuzzification equation is used to determine the crisp total scores of individual locations.

$$d(\tilde{f}_i) = \frac{1}{4}(s_i + t_i + u_i + v_i) \qquad i = 1,2,\ldots,m \quad (14)$$

where $d(\tilde{f}_i)$ gives the defuzzified value (crisp value) of the total fuzzy score of location alternative A_i. Table 9 shows the aggregated fuzzy score and the defuzzified total score.

Table 7: Fuzzy rating matrix

Attributes	Achham	Bhojpur	Dadeldhura	Gulmi	Illam	Khotang	Mahottari	Okhaldhunga	Pyuthan	Ramechhap	Salyan	Tanahu
C1	39.38	37.50	42.50	50.63	45.00	39.38	58.13	37.50	48.13	46.88	39.38	60.00
	58.13	56.25	61.25	70.63	63.75	58.13	76.88	56.25	65.63	66.88	58.13	80.00
	70.63	71.25	71.88	76.25	72.50	66.88	85.00	71.25	66.88	70.63	67.50	88.13
	89.38	87.50	89.38	96.25	91.25	85.63	95.00	87.50	85.63	90.63	87.50	98.13
C2	22.50	31.88	15.00	22.50	26.25	18.75	49.38	22.50	16.88	28.13	16.88	28.13
	40.00	49.38	31.25	42.50	46.25	37.50	69.38	42.50	35.63	45.63	35.63	46.88
	41.25	58.13	45.00	55.63	57.50	60.00	80.63	56.25	48.75	58.13	44.38	54.38
	60.00	75.63	65.00	75.63	77.50	77.50	94.38	73.75	68.75	75.63	63.13	74.38
C3	54.38	51.88	53.75	55.63	53.75	50.63	39.38	48.75	54.38	54.38	52.50	57.50
	74.38	71.88	73.75	75.63	73.75	70.63	59.38	68.75	74.38	74.38	72.50	77.50
	86.25	80.63	78.13	82.50	83.13	79.38	74.38	81.25	79.38	79.38	79.38	84.38
	100.00	98.13	94.38	100.00	98.13	98.13	90.63	100.00	98.13	98.13	98.13	98.13
C4	53.13	47.50	52.50	51.88	58.75	41.25	58.13	43.13	50.63	50.63	37.50	56.25
	73.13	67.50	72.50	71.88	78.75	61.25	78.13	63.13	70.63	70.63	57.50	76.25
	80.63	76.25	82.50	79.38	83.75	74.38	85.63	76.25	79.38	79.38	80.00	88.13
	98.13	92.50	96.25	94.38	96.25	94.38	98.13	96.25	98.13	98.13	96.25	98.13
C5	50.63	45.00	50.63	51.88	50.63	45.00	63.13	45.00	50.63	48.75	46.25	56.25
	70.63	65.00	70.63	71.88	70.63	65.00	83.13	65.00	70.63	68.75	66.25	76.25
	84.38	74.38	82.50	81.25	84.38	74.38	85.00	78.13	79.38	81.25	79.38	86.25
	98.13	94.38	100.00	100.00	98.13	94.38	100.00	98.13	98.13	100.00	98.13	100.00
C6	43.13	31.88	46.88	45.00	41.25	39.38	40.63	45.00	39.38	37.50	38.57	45.00
	63.13	51.88	66.88	65.00	61.25	58.13	58.13	65.00	59.38	57.50	57.14	65.00
	75.63	70.00	75.63	75.63	80.63	65.63	73.13	72.50	72.50	74.38	77.86	73.13
	86.88	88.75	90.63	94.38	94.38	85.63	86.88	88.75	88.75	90.63	93.57	90.63
C7	54.38	58.13	58.13	56.25	55.63	52.50	54.38	56.25	58.13	56.25	52.50	56.25
	74.38	78.13	78.13	76.25	75.63	72.50	74.38	76.25	78.13	76.25	72.50	76.25
	86.25	81.88	86.25	81.88	83.75	80.63	83.75	82.50	81.25	83.75	79.38	84.38
	100.00	98.13	100.00	98.13	100.00	98.13	100.00	100.00	100.00	100.00	98.13	98.13
C8	53.13	49.38	54.38	50.63	57.50	52.50	60.00	56.25	56.25	56.25	52.50	54.38
	73.13	69.38	74.38	70.63	77.50	72.50	80.00	76.25	76.25	76.25	72.50	74.38
	86.88	78.75	87.50	83.75	84.38	83.13	85.63	83.13	83.13	83.13	81.25	83.75
	98.13	96.25	100.00	96.25	98.13	98.13	98.13	98.13	98.13	98.13	96.25	100.00

Step 5: Determine the order of establishment of the MLHs.

Finally, to determine the order of establishment of MLHs, we rank the location alternatives based on the crisp values. The location alternatives with larger crisp values should be established first, followed by the location alternatives with lower values. The higher crisp value indicates the better performance of alternatives over the selected attributes. Table 8 shows the order of the establishment of 12 selected MLHs. Based on the defuzzified total score, the order of establishment should follow the establishment of first MLH in Mahottari district which is then followed by Tanahu, Illam, Gulmi, Ramechhap, Dadeldhura, Achham, Pyuthan, Okhaldhunga, Bhojpur, Salyan and Khotang districts.

Table 8: Aggregated fuzzy score, defuzzified total score, and order of establishment

MLH alternatives	Aggregated fuzzy score				Defuzzified total score	Order of establishment
Mahottari	52.95	72.42	81.67	95.36	75.60	I
Tanahu	52.42	72.29	81.08	95.18	75.24	II
Illam	49.00	68.82	79.16	94.58	72.89	III
Gulmi	48.75	68.75	77.47	94.86	72.46	IV
Ramechhap	47.64	67.39	76.55	94.27	71.46	V
Dadeldhura	47.46	66.90	76.84	92.54	70.93	VI
Achham	46.74	66.31	77.15	92.02	70.56	VII
Pyuthan	47.45	66.97	74.25	92.38	70.26	VIII
Okhaldhunga	44.62	64.44	75.44	93.11	69.40	IX
Bhojpur	44.23	63.80	74.20	91.66	68.47	X
Salyan	42.37	61.87	74.27	92.04	67.64	XI
Khotang	42.80	62.33	73.05	91.59	67.44	XII

3D concept model of a Mobile Logistic Hub.

4. Discussion and recommendations

To understand the location selection process, we dissect the performance of the 59 candidate MLHs selected in this study. The 59 MLH candidates can further be categorized based on their performance over coverage distance and constraint satisfaction. Among the 59 candidates, 19 candidate MLHs located in Baglung, Bajhang, Bajura, Darchula, Dolpa, Humla, Jajarkot, Jumla, Kalikot, Manang, Mugu, Mustang, Myagdi, Rasuwa, Rukum East, Rukum West, Sankhuwasabha, Solukhumbu and Taplejung districts satisfy the coverage requirement, 20 candidate MLHs located in Arghakhanchi, Bara, Bardiya, Bhaktapur, Chitwan, Dailekh, Dhading, Dhankuta, Kapilbastu, Kavrepalanchok, Lalitpur, Nawalpur, Nuwakot, Parasi, Parbat, Rautahat, Saptari, Sindhupalchok, Syangja and Terhathum districts satisfy the three constraints set and only 12 candidate MLHs located in Achham, Bhojpur, Dadeldhura, Gulmi, Illam, Khotang, Mahottari, Okhaldhunga, Pyuthan, Ramechhap, Salyan, and Tanahu districts satisfy both coverage requirement and all three constraints set. Therefore, the model selected the 12 MLHs to cover the 21 PODs located in Achham, Bajura, Bhojpur, Baitadi, Dadeldhura, Doti, Gulmi, Illam, Panchthar, Khotang, Dhanusa, Mahottari, Sindhuli, Okhaldhunga, Solukhumbu, Pyuthan, Rolpa, Ramechhap, Rukum west, Salyan, and Lamjung districts leaving 11 PODs located in Bajhang, Darchula, Dolpa, Humla, Jajarkot, Jumla, Kalikot, Mustang, Rukum East, Sankhuwasabha and Taplejung uncovered. Detailed information on the performance of candidate MLHs is presented in Table 10 in Appendix.

We further explore on how the 11 uncovered PODs can be encompassed within the emergency preparedness strategy. Accommodating the 11 PODs could require relaxation of either or both of the constraints imposed in the mathematical model. The 11 uncovered PODs also repeat themselves as the candidate MLHs, a closer observation at the performance of these candidate MLHs reveals that all the 11 PODs perform poorly especially in terms of transportation accessibility. Furthermore, MLH candidates at Bajhang and Kalikot districts perform poorly in terms of level of development and MLH candidate at Rukum East has composite disaster vulnerability close to the maximum value. As such we performed a sensitivity analysis to identify the sensitivity of the mathematical model to the coverage distance. Upon increasing the coverage distance to 150 km, POD located in Sankhuwasabha can be covered either by MLH candidates located in Dhankuta or by Terhathum with Dhankuta corresponding to a lower inter-node distance while rest of the PODs remain uncovered. Increasing the coverage distance to 200 km did not contribute to additional coverage. Further increase of coverage distance to 300 km resulted in coverage of additional PODs located in Jajarkot, Jumla, and Kalikot districts by MLH candidate in Dailekh and POD in Mustang by Nawalpur and Syangja districts.

It is noteworthy that the 11 PODs uncovered by the MLHs within the scope of this study are all located in remote areas of Nepal. As a consequence, they are difficult to access even during normal situation. Nonetheless, a portion of approximately 1.34 million

Table 9: Order of establishment of four MLHs

MLH alternatives	Defuzzified total score	Order of establishment	Cumulative population covered
Mahottari	75.60	I	1,6785,49
Tanahu	75.24	II	167,724
Illam	72.89	III	482,071
Gulmi	72.46	IV	280,160
Ramechhap	71.46	V	202,646
Dadeldhura	70.93	VI	604,738
Achham	70.56	VII	392,389
Pyuthan	70.26	VIII	452,608
Okhaldhunga	69.40	IX	253,870
Bhojpur	68.47	X	182,459
Salyan	67.64	XI	346,728
Khotang	67.44	XII	206,312

population living in these districts are still vulnerable to the three major disasters. As short-term solution to improve coverage to these districts, concerned authorities may consider: 1) establishing additional MLHs in these districts by relaxing the three constraints while putting efforts to improve the accessibility to and from these districts in general, and 2) increasing the coverage distance. It is important to note that both the improvement measures have associated weaknesses, for example establishing a MLH in a location with poor accessibility may lead to difficulty in movement, handling, and distribution of emergency relief materials in case of a disaster occurring, stagnation of the established MLH due to operational unsustainability etc. whereas increase in coverage distance will lead to decreased service level. Long term and more sustainable approach to cover 11 PODs should focus on 1) improving the road access and connectivity to other districts for solving accessibility issue, 2) improving education, health quality and creating employment opportunities which will ultimately upgrade HDI and, 3) deploy disaster prevention and mitigation strategies to reduce CDVI.

The interviews with the decision makers revealed a difference in their decision opinion. There is not a single instance in which the decision opinion is same for any single attribute or a location alternative. This highlights the significance of incorporating multiple decision makers in the decision making process such that an inclusive result be obtained. Overall availability of open spaces, proximity to disaster vulnerable districts and support from the local government were found to be the three most important attributes among the eight attributes. Although, airlift was one of the main modes of relief delivery especially to the remote areas during Nepal earthquake 2015, the results of the interview with the decision makers revealed lowest importance being given to the attribute proximity to the airport. Based on the 11 decision makers' perceived performance of 12 MLH locations over the eight selected attributes, the order of establishment was obtained. The order of establishing four MLHs should follow Mahottari, Tanahu, Illam and Gulmi as shown in Table 9. These four MLHs have higher defuzzified total score suggesting that they perform better over the eight attributes. The four MLHs cover 49.68 percent of the total population which can be covered by the 12 MLHs.

Conclusion

In this study, we determined the optimal number and locations of MLHs by utilizing the MCLP as an integer task considering three sudden-onset disasters: earthquake, landslide, and flood which combined has the highest frequency of occurrence among all types of natural disasters in Nepal; in addition, they often claim a large number of lives and damage infrastructure. The model identified 12 MLHs to be established in Achham, Bhojpur, Dadeldhura, Gulmi, Illam, Khotang, Mahottari, Okhaldhunga, Pyuthan, Ramechhap, Salyan, and Tanahu districts for preposition of MSUs. The 12 selected MLHs cover 21 PODs within a coverage distance of 100 km. Based on the current resources available with WFP at the moment, the four MLHs should be established in Mahottari, Tanahu, Illam and Gulmi districts.

Expert evaluation of the eight attributes by 11 decision-makers belonging to different governmental and non-governmental organizations revealed highest degree of importance associated with attributes availability of open spaces for establishing MLH with a total score of 0.15 which is followed by attributes proximity to disaster vulnerable districts and support from local government as the second most important attributes with scores of 0.14 each. Availability of utility infrastructure ranks as the third important attribute followed by availability of labor and level of safety in the candidate sites, proximity to armed forces disaster management and proximity to the airport. The result suggests that proximity to the airport has the least significance in selecting the MLH location. The order of establishment of 12 MLHs should follow with the establishment of first MLH in Mahottari which is then followed by Tanahu, Illam, Gulmi, Ramechhap, Dadeldhura, Achham, Pyuthan, Okhaldhunga, Bhojpur, Salyan and Khotang districts. The first four to be established should be Mahottari, Tanahu, Illam and Gulmi districts which combinely covers 49.68 percent of the total population under MLH influence.

Our study has some limitations that should be addressed in future work. The results of the study provide the locations for placing MLHs at the headquarter of the district without in-depth knowledge of availability of workable open space within the vicinity of the district headquarter. Although multiple expert's judgement was obtained via interviews, subjectivity and possible bias is inevitable. Further data and analysis will be required to determine the precise locations. Distances are calculated between each district headquarters and these headquarters are assumed to have proper road access to and from the demand nodes. The study does not consider demand coverage provided by warehouses owned by entities other than the Government of Nepal, World Food Programme (WFP), and Nepal Red Cross Society in Nepal merely due to the lack of data. Overall, the results of the study are purely based on the data available during the study period, therefore having updated data could possibly improve the quality of the results. Finally, in this study, decision makers are considered to be homogeneous which might not be the case in reality, further exploration on the true nature of decision-making is desired to identify the globally acceptable order of establishing MLHs.

Future research could identify the warehouses presently existing in Nepal to provide a deeper understanding on segregated/overlapping coverage arrangement existing in the country and need for restructuring existing network configuration. Further extension of this study can also focus on how sourcing can be linked to the established MLHs by realization of multiple-disaster scenarios in terms of demand, transport accessibility and travel time. The location and sourcing strategies may change under the new network configuration. With slight modifications, this model can be similarly replicated for other vulnerable countries. Its applicability is not limited to determining warehouse locations to pre-position inventories for disaster relief distribution; with some adjustments and improvisation, the model can also be used to determine locations for search-and-rescue centres, emergency medical centres, etc. With adjustment, the same technique can be applied to determine locations for facilities for both military and civilian purposes (including public facilities like fire stations or health centres). In conclusion, we hope that researchers will be able to use our findings to enhance disaster response in vulnerable countries.

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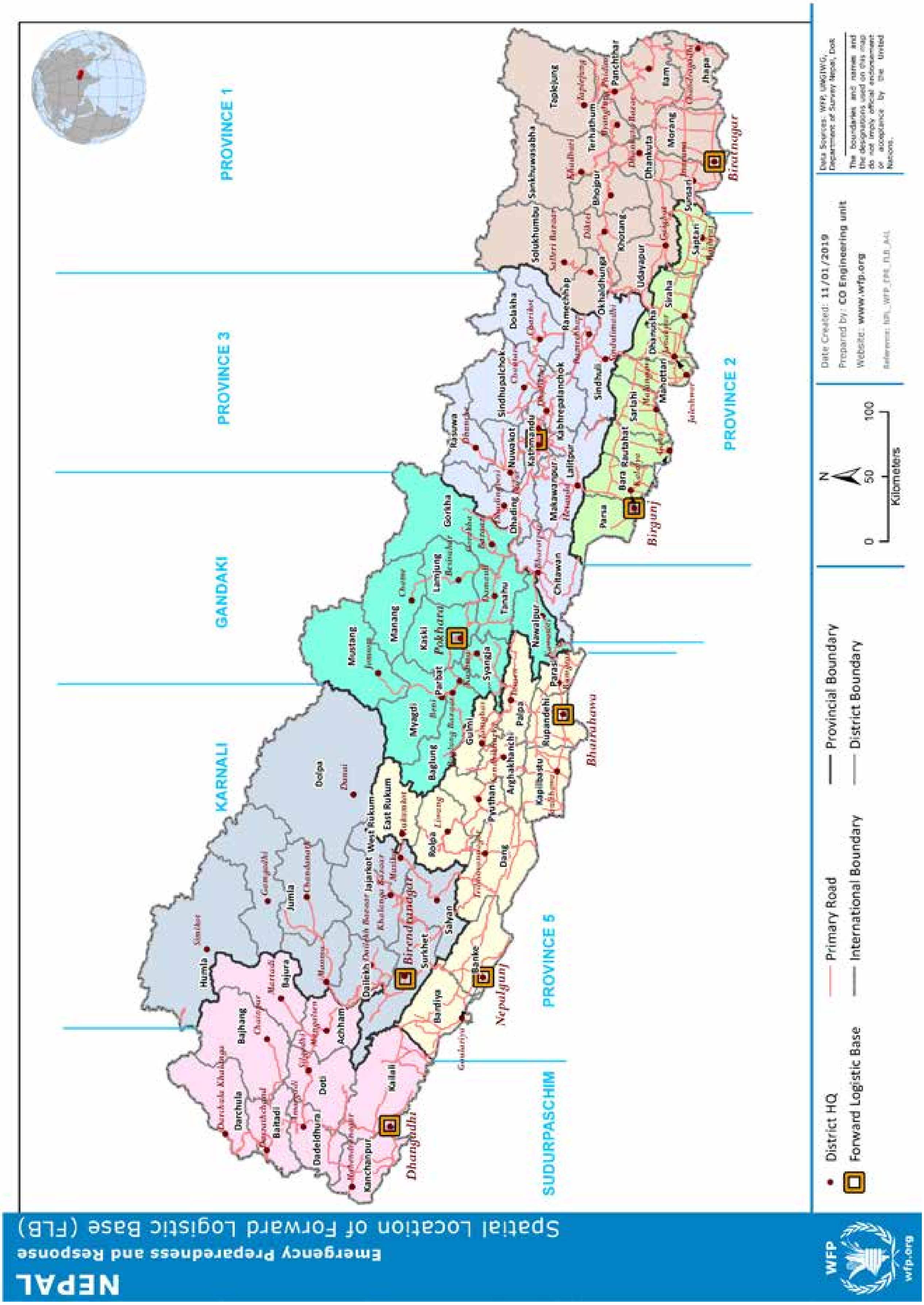
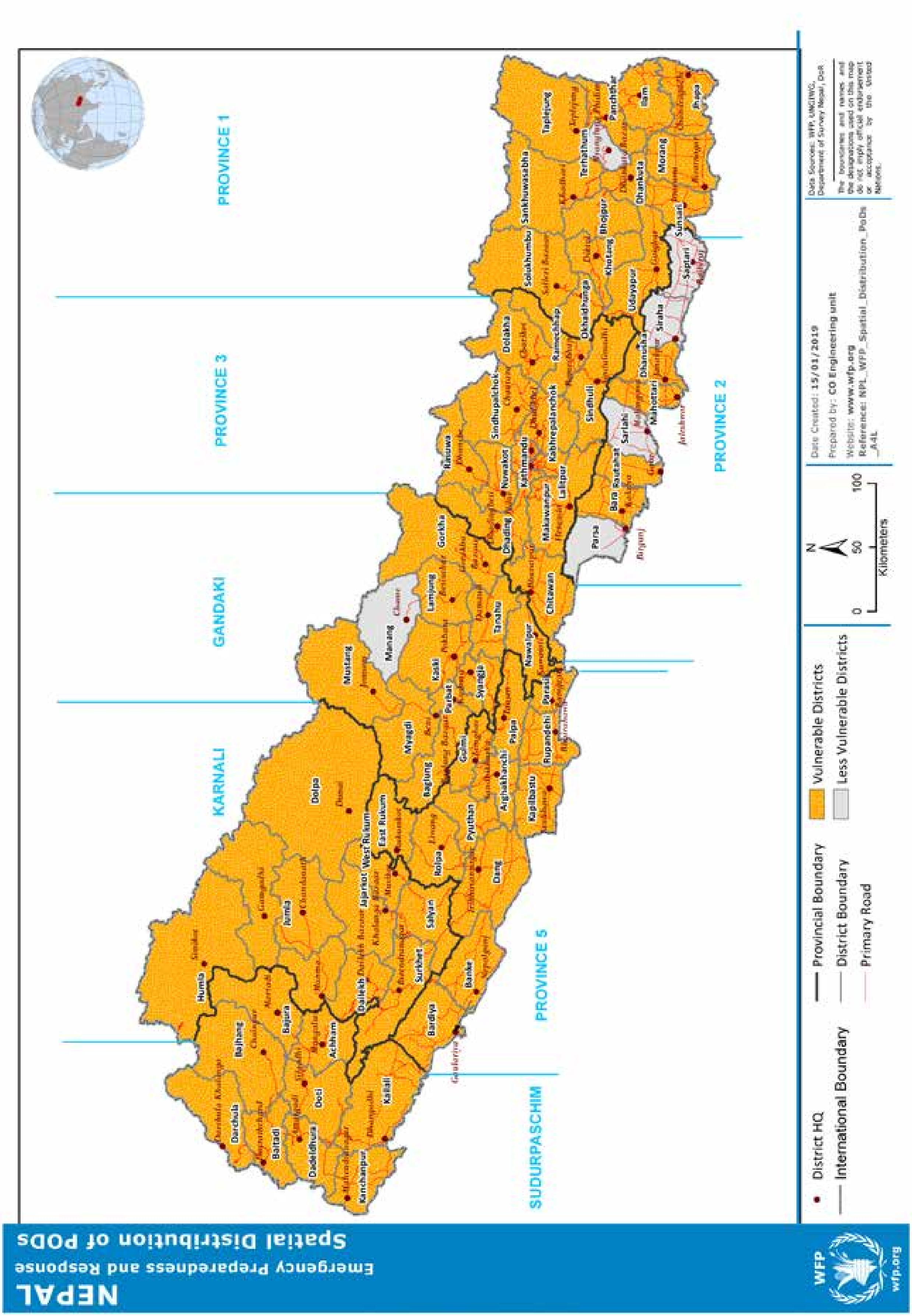
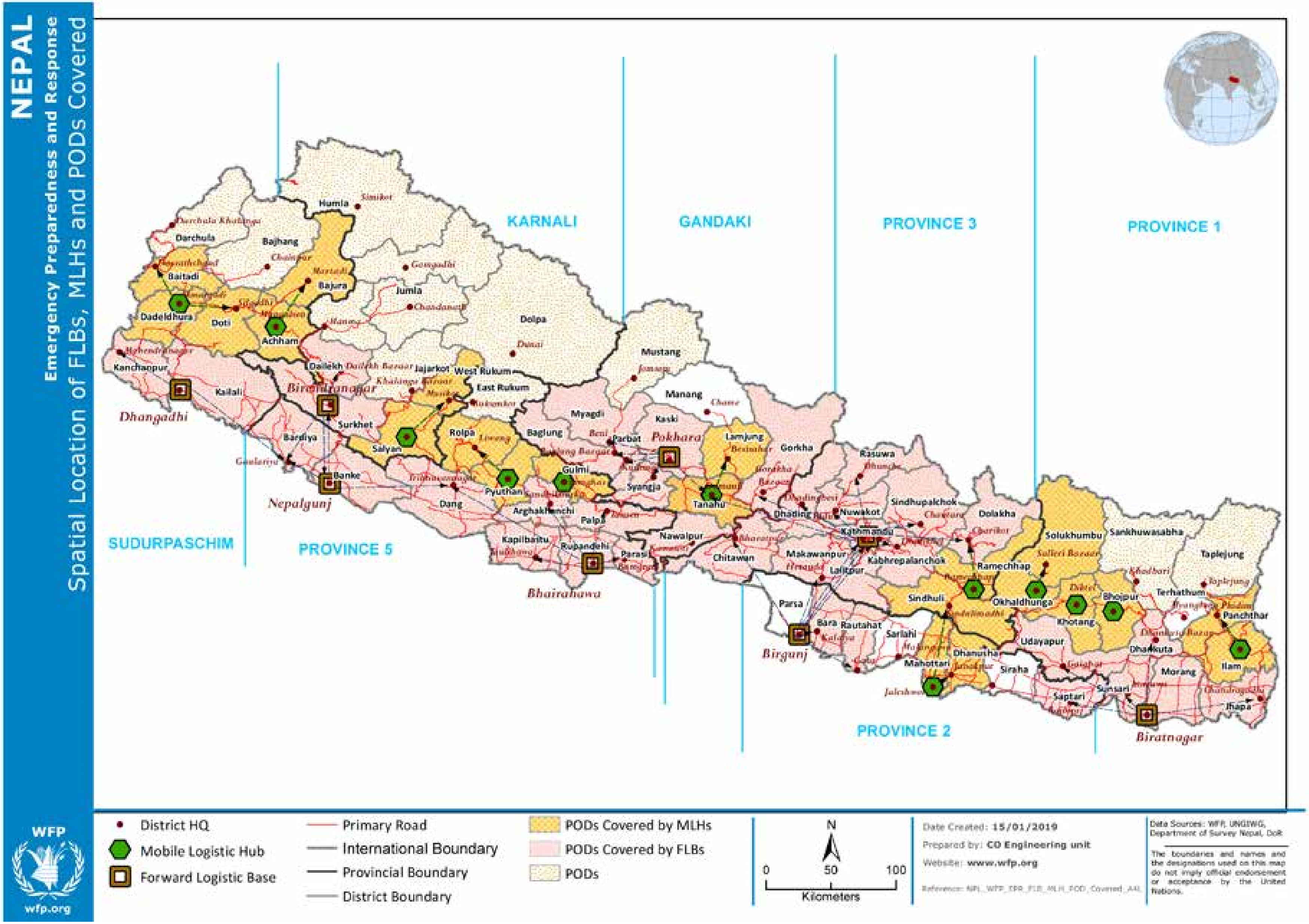
Annex-I: Spatial Location of Forward Logistic Base (FLB)



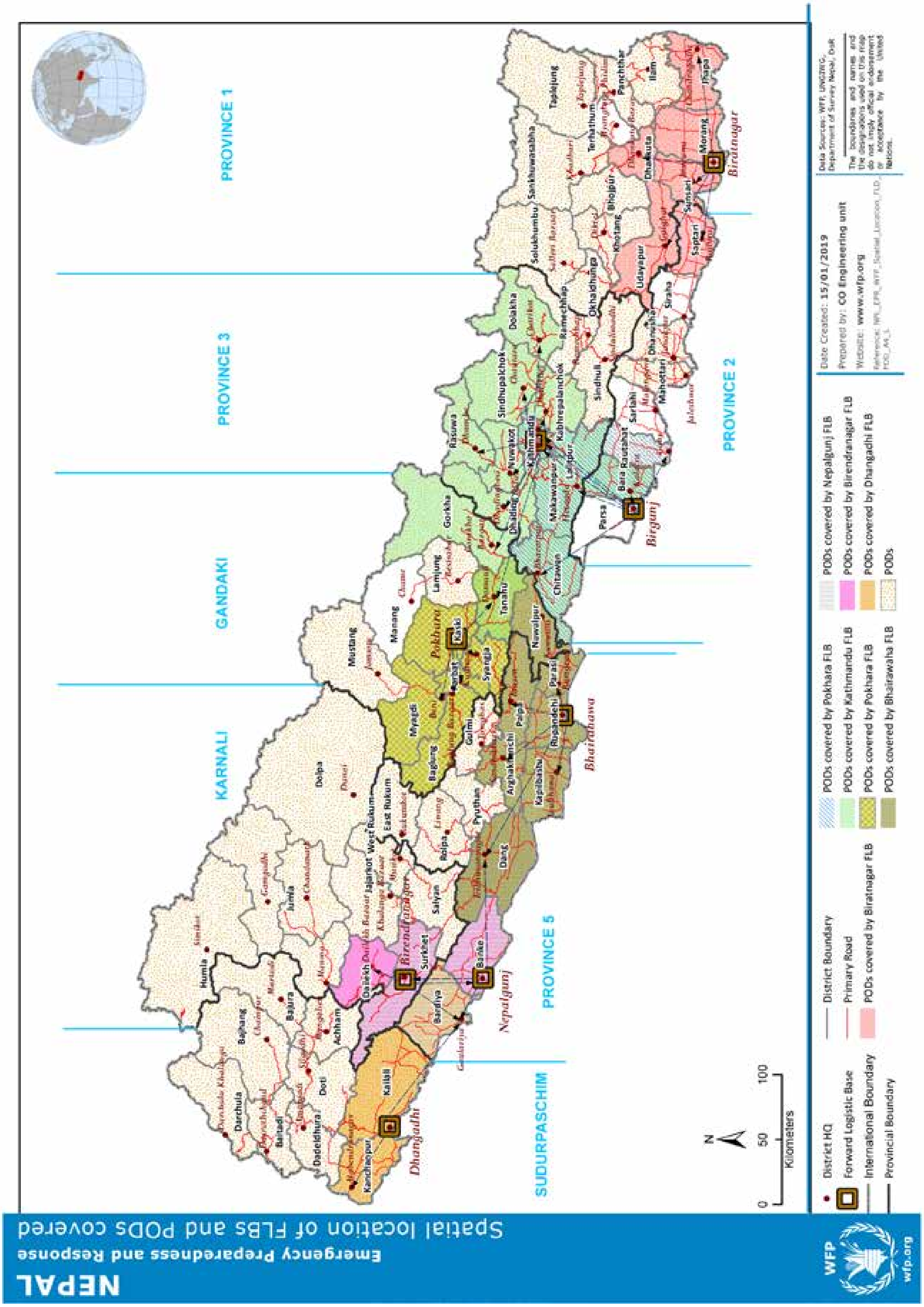
Annex-II: Spatial Distribution of PODs



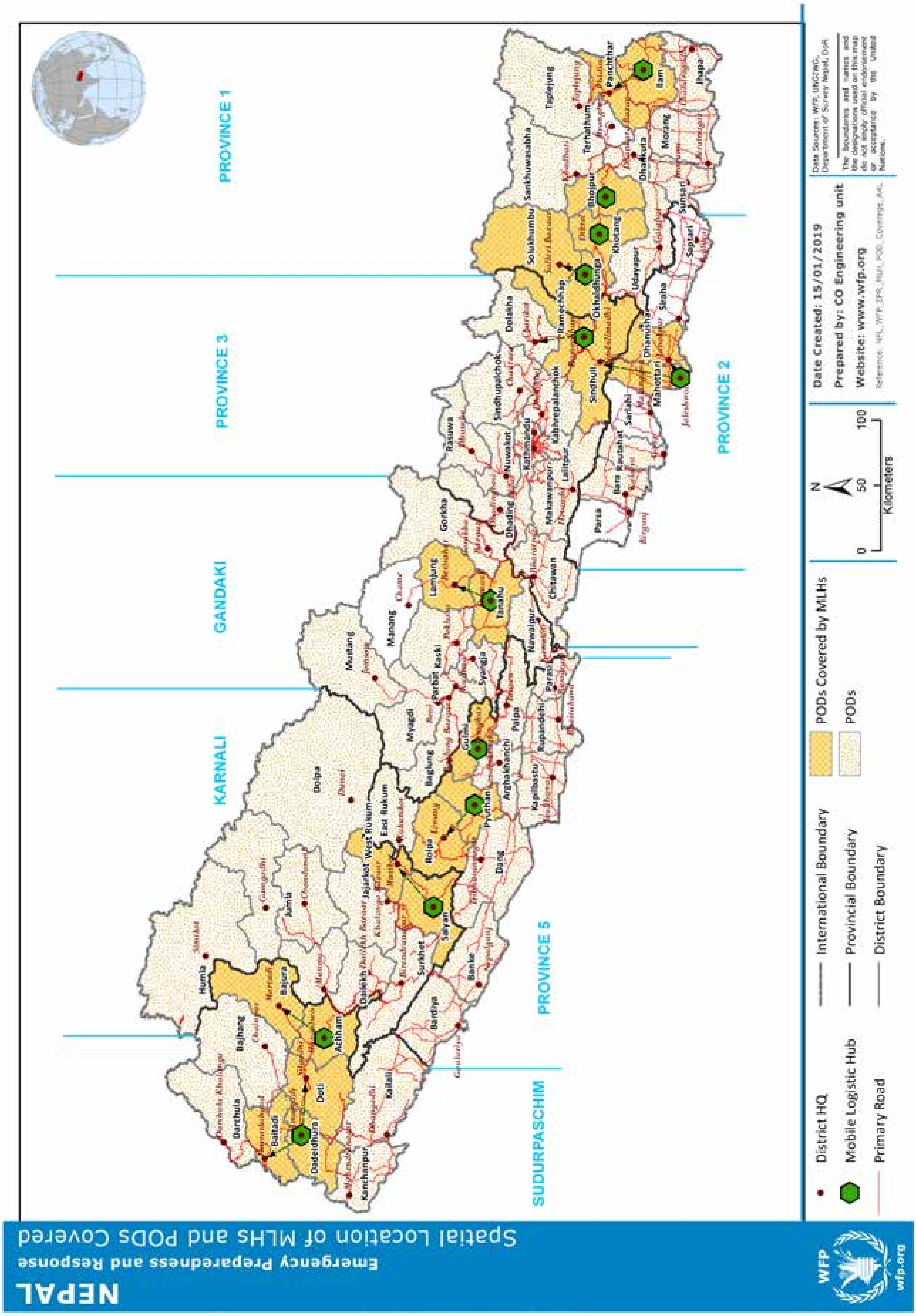
Annex-III: Spatial Location of FLBs, MLHs and PODs Covered

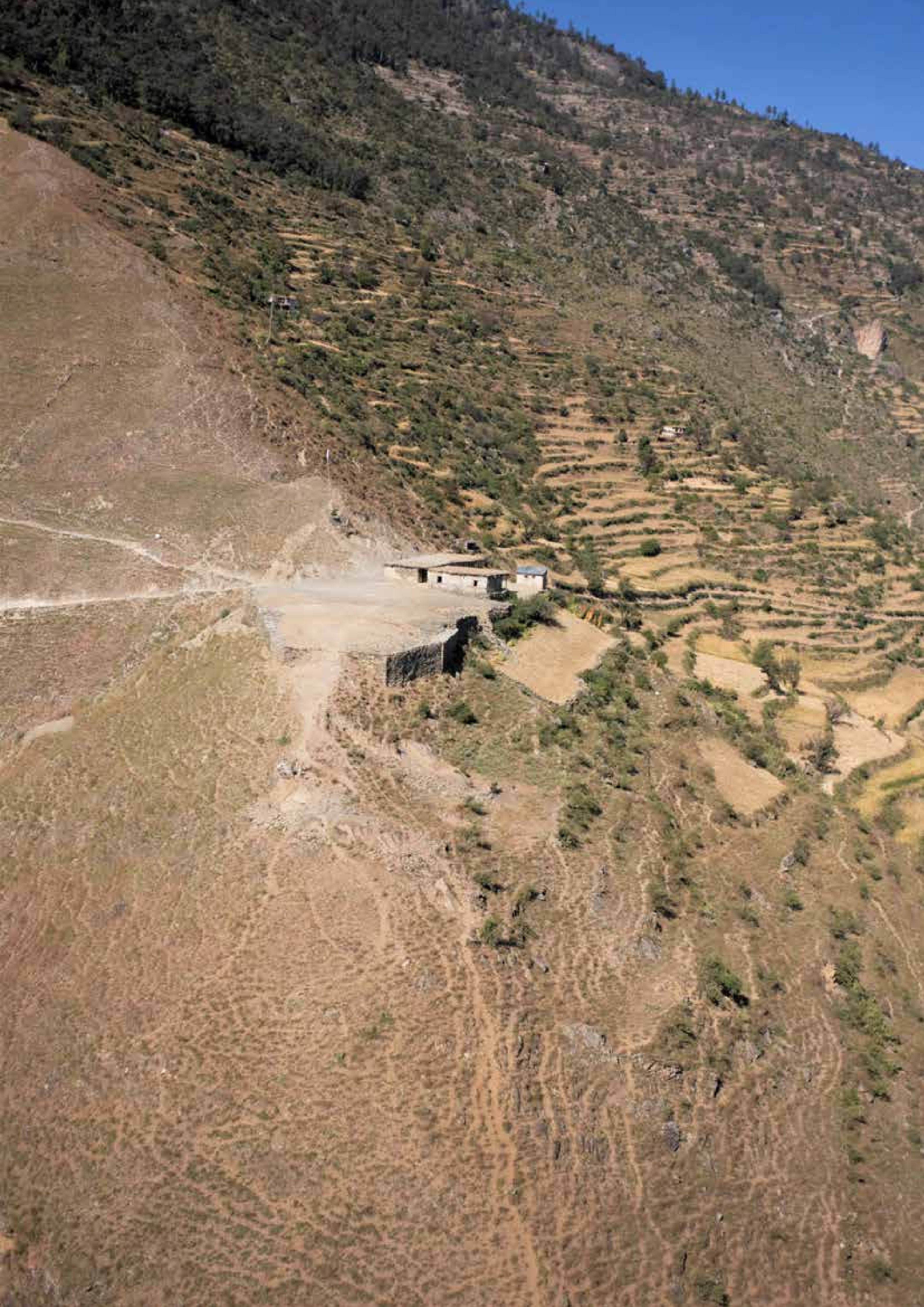


Annex-IV: Spatial location of FLBs and PODs covered



Annex-V: Spatial Location of MLHs and PODs Covered





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