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REPAIR SEQUENCE AND RECOVERY TIME IN WATER DISTRIBUTION NETWORK RESILIENCY

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ABSTRACT: Recent disasters highlighted that Water Distribution Systems (WDS) suffered greatly during seismic events. But people cannot afford to have extended water service interruption as it is essential for drinking, sanitation, and health. Thus, it is imperative that WDS provides adequate resistance to extreme events. And in the event of failure, it must recover back its functionality within short period. Resilience-based engineering ensures that infrastructures be robust to adequately resist seismic events and recover from failure fast. It also requires to have resources and redundant systems. This implies that WDS must satisfy resiliency requirements for it to function satisfactorily during and after seismic events. This study quantifies the resiliency of La Trinidad Water District (LTWD) through measuring the impacts of restoration sequences to recovery duration and knowing which sequence satisfies resiliency. LTWD, in Benguet, Philippines, is at risk to earthquake due to geologic and geographic setting, thus, it must be "resilient". In this study, restoration strategies were conducted using constrained spanning trees to determine the most efficient network connectivity. Horn's algorithm was applied to find the most efficient repair sequence. Results showed that restoration sequence is directly related to rapidity of resiliency. The shortest restoration resulted to a faster recovery to return back to its pre-event system functionality. For LTWD, restoration will take 8.62 days for full recovery.

Keywords: Resilience, Horn's algorithm, Restoration curve, Earthquake, Water distribution network

1. INTRODUCTION

The Philippine Institute of Volcanology and Seismology (PHIVOLCS) [1] considered the province of Benguet to be, among the provinces in the Philippines, the third-most at risk to earthquakes considering its geologic and geographic setting. According to Mines and Geosciences Bureau (MGB) [2], La Trinidad - a municipality in Benguet is highly vulnerable to geologic hazards because of several active fault lines in the area. This makes the water infrastructure vulnerable to earthquake hazards.

Water distribution Networks (WDN) had demonstrated vulnerability against seismic events [3-5]. People are dependent on water for drinking, sanitation, and health. Hence, any water interruption could have a tremendous impact to the public. This motivated the researchers to assess the resiliency of a local water network in case of a seismic event. The study of [6] had demonstrated the use of repair sequencing for a local water distribution network using Graph theory and Horn's algorithm. Thus, despite the difference in the geologic and geographic setting of this study area, the researchers will employ the same methodology then relate it to the water network's resiliency.

The case study area is La Trinidad Water District (LTWD), located in La Trinidad in the province of Benguet (Fig.1). La Trinidad is where Baguio City is located. Baguio city is considered to be the summer capital of the Philippines due to its cold weather and has become one of the country's top tourist destinations. LTWD is a local water district that serves 16 barangays with drinking water. It has been in operation for more than 30 years but has not received any technology-based upgrade yet. Its only upgrade is the continuous expansion of water pipe networks to serve a rapidly increasing demand. It has also increased its water sources, from four to seventeen comprised of mixed spring and deep well sources. La Trinidad was devastated by a magnitude 7.8 earthquake in 1990 where casualties and damage to the structure is considered to be among the deadliest earthquake that hits the country [7].

The area is surrounded by five active major faults: Philippine fault, Digdig fault, San Manuel fault, Tebbo fault, and Tubao fault. LTWD was fortunate to be spared suffered from any major damage during the 1990 earthquake. Though there were reports of few pipe breakages due to joint pullout from the main transmission line, these were repaired immediately.

Because of great risks that earthquake hazard poses to the area of La Trinidad, it is important to

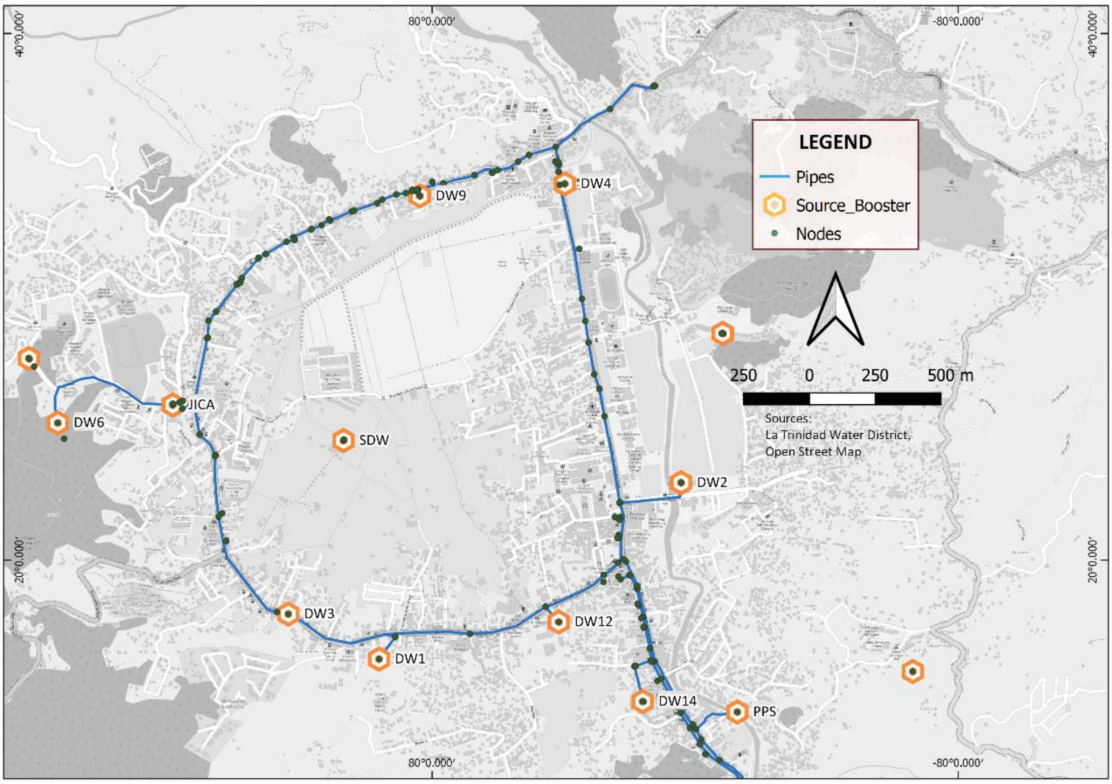

Fig.1 Schematic diagram of La Trinidad Water District (LTWD)

for LTWD to satisfy water distribution network resiliency as it is of utmost importance that water supply remains functional during earthquake events for life safety, rescue, and healthcare operations. Hence, this study conducted the following: assessment of the possible impact of earthquake hazard to LTWD, and evaluation of post-earthquake restoration strategy to ensure that the functionality of LTWD can return to its pre-event functionality at the soonest possible time.

2. THEORETICAL BACKGROUND

Graph theory [8,9] was employed to perform algorithmic calculations on the water distribution network. Specifically, *G = (V, E)* corresponds to a network configuration of a water pipeline system, where the elements *V* are the demand nodes and the elements *E* are the pipelines or the links between nodes. A series of single-rooted trees, which are finite directed graphs with no loops and with distinguished root nodes (i.e. supply nodes of the network) and whose union contain all the vertices in V represents a spanning forest of the network. Once the rooted trees are obtained, Horn's algorithm [10] is used to find an optimal repair sequencing of seismically damaged pipelines.

Once the rooted trees are obtained, Horn's algorithm [10] is used to find an optimal repair sequencing of seismically damaged pipelines [11] of the LTWD. In the repair sequence, priority is given to demand nodes with higher efficiency. This is to restore service first to nodes that will supply water to more consumers in the shortest time possible.

In optimizing the restoration process, the study utilized a restoration function which is a time-dependent function representing the degree of restoration with respect to time. Suppose $\sigma(j)$ is the position number of node j in the recovery sequence and t_j is the time required to repair each damaged unit j. Define T_j as

$$T_j = \sum_{\sigma(k)\leq\sigma(j)} t_k \tag{1}$$

The restoration curve *R(Tj)* is a stepwise function defined by the following equation:

$$R(Tj) = \sum_{\sigma(k)\leq\sigma(j)} h_k / \sum_{i=1}^{n} h_i \tag{2}$$

where h_i represents the number of users that are linked to demand each node v_j restored at time T_j after an earthquake event and $n = |V|$.

Using Horn's algorithm [10], an optimized restoration sequence for damaged LTWD during a

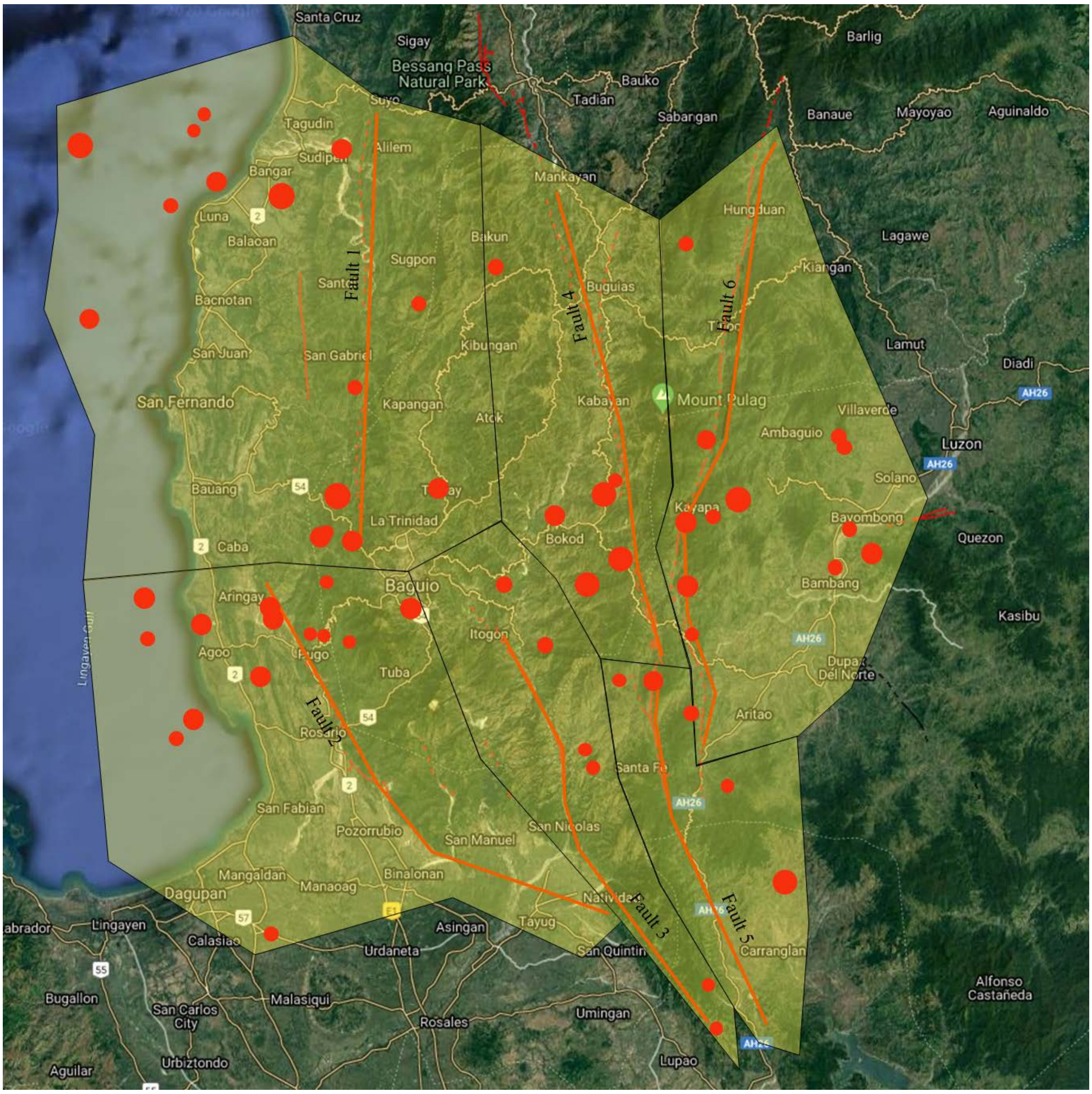

Fig.2 Faults surrounding the study area (source of map: https://hazardhunter.georisk.gov.ph/map)

seismic event is achieved. In sequencing the repair of nodes, priority is given to demand nodes with higher efficiency. This is to restore service first to nodes that will supply water to more consumers in the shortest time possible.

Global optimization, through Horn's algorithm, is done by minimizing the area above the restoration curve. This is achieved using the improved efficiency parameter, γ_j*, and is computed by:

$$\gamma_j^* = \sum_{i\in U(j)} h_i / \sum_{i\in U(j)} t_i \quad (3)$$

where *U(j)* is a subset of a set of nodes reachable from node v_j. It is determined so that γ_j* takes on the greatest value. The improved efficiency is taken along a directed path from supply nodes on a single line. Obviously, there are no directed cycles.

The area above the restoration curve, called the linear delay penalty, is computed as follows:

$$t_A = \sum_{i=1}^{n} h_i T_i \,/\, \sum_{i=1}^{n} h_i \quad (4)$$

t_A represents the average time for restoration and can be regarded as the measure of the overall impact of lifeline malfunction.

3. METHODS, ANALYSIS, AND RESULTS

In conducting the Probabilistic Seismic Hazard Analysis (PSHA), seismic sources that will significantly influence the study area are the ones considered. Hence, foreshocks and aftershocks are not considered, earthquakes with magnitude less than 5.0 were removed, and only earthquake events within a 100-kilometer radius are evaluated.

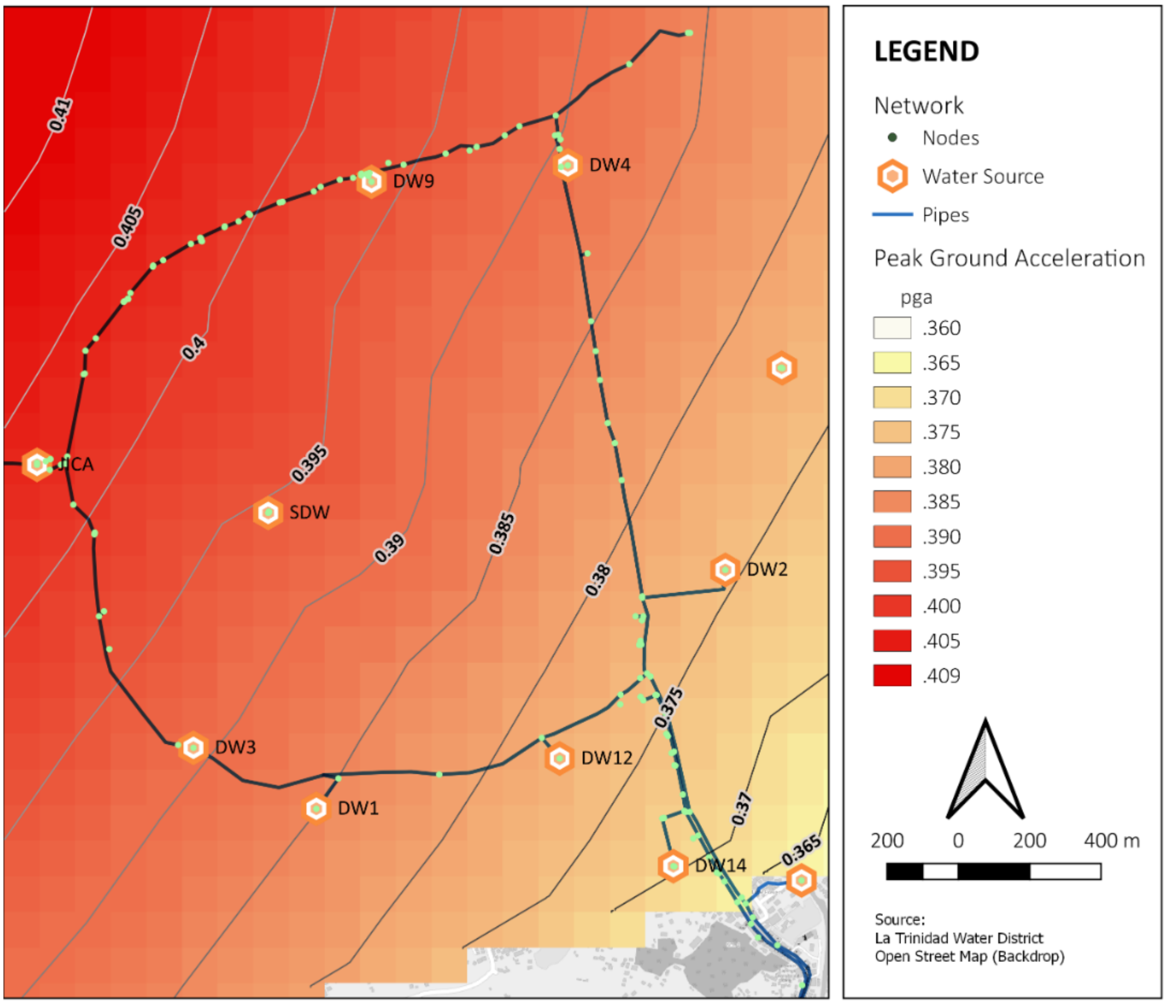

Fig.3 PGA (Peak Ground Acceleration) contour map as a fraction of g

Moreover, only six seismic sources are considered (Fig.2). These faults were divided into 100-meter segments and distances are measured from a point on the fault to a point on the grid. This is necessary to determine the probability of radius for each seismic zone.

Gutenberg-Richter equation [12] was used to generate the magnitude and frequency of the earthquakes from the six seismic sources mentioned. To translate PSHA output into a Peak Ground Acceleration (PGA) map, the LTWD seismic map was subdivided into grids and points. For ground motion prediction, Youngs, Chiou, Humphrey, and Silva [13] ground motion prediction equation was used. The resulting PGA contour map was shown in Fig.3. It can be observed that PGA only ranged from a maximum of 0.409g to a minimum of 0.365g. Hence, this range is very narrow which validates the assumption that all pipes can fail during a seismic event.

The study's delimitation considered only the main transmissions that were laid out along the highway. This also caused many of the other water sources of LTWD to be excluded because they do not contribute to the transmission main. Hence, in the development of the schematic network model, for the optimization of repair sequencing, only a single supply source is applicable. The schematic diagram of the simplified network model is shown in Fig.4.

The rate of repair for the damaged pipes was taken as 1 kilometer of pipe-length per day The schematic diagram (Fig.4) shows six trees, all rooted at node 1. Among these trees, the node in the tree with higher total efficiency is repaired first, followed by the next higher efficiency. This repair sequence goes on until all nodes are restored.

The result of the repair sequence is shown in Table 1 and it is derived after imposing Horn's algorithm. In this table, nodes were arranged based on the repair sequence. The improved efficiency

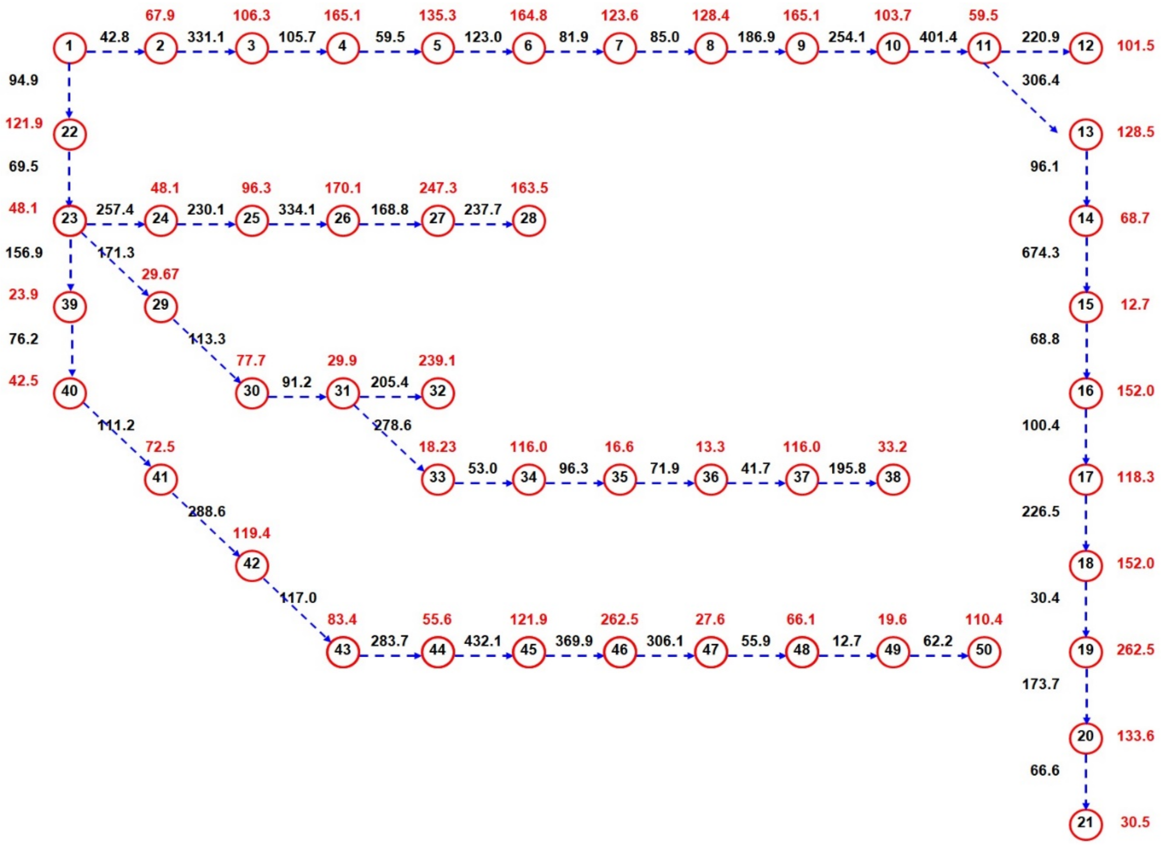

Fig.4 LTWD repair scheme model showing repair time (red font) and node demand (black font)

parameter is also shown. The total time of restoration is 8.62 days (Fig.5). So, an all-pipe failure scenario will only take approximately 9 days to repair and bring back the water distribution network to its original pre-event functionality.

Table 1 Horn’s algorithm sequencing and efficiency parameter

Sequence	Node	γ*	Sequence	Node	γ*	Sequence	Node	γ*
1	22	0.73	18	8	0.57	35	42	0.45
2	2	0.70	19	9	0.54	36	43	0.46
3	3	0.68	20	10	0.51	37	44	0.44
4	4	0.76	21	11	0.52	38	45	0.49
5	5	0.69	22	13	0.61	39	46	0.60
6	23	0.65	23	14	0.65	40	47	0.51
7	29	0.65	24	15	0.64	41	48	1.50
8	30	0.85	25	16	1.27	42	49	1.74
9	31	0.91	26	17	1.17	43	50	1.78
10	32	1.16	27	18	1.16	44	33	0.42
11	6	0.63	28	19	1.58	45	34	0.64
12	7	0.60	29	20	0.68	46	35	0.44
13	24	0.59	30	12	0.46	47	36	0.53
14	25	0.70	31	21	0.46	48	37	0.63
15	26	0.78	32	39	0.44	49	38	0.17
16	27	1.01	33	40	0.46			
17	28	0.69	34	41	0.46			

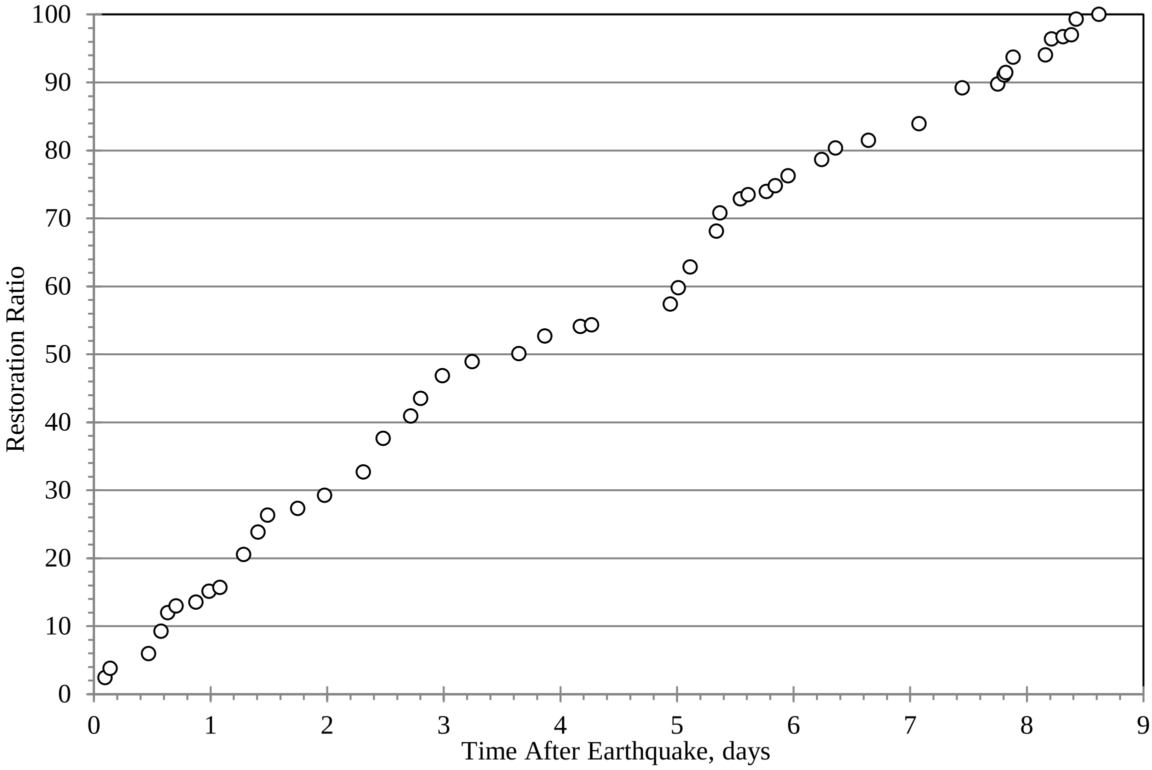

Fig.5 Restoration curve for LTWD during a seismic event using Horn's algorithm

4. CONCLUSION

The six identified seismic sources can potentially damage and disrupt water supply service provided by La Trinidad Water District (LTWD). Based on PSHA, the north-western part of the municipality will experience the highest PGA implying that pipes located in that area will be highly vulnerable to damage due to earthquake. Moreover, about 3 kilometers (37.5%), serving about 39% of total demand, of the pipe network is projected to be damaged based on PGA derived from PSHA. Utilizing the average time for restoration (t_A) based on Horn's algorithm resulted to a t_A value of 3.95 days with a total restoration time of 8.62 days. In an event where earthquake causes an all-pipe-failure, following the repair sequence as derived from Horn's algorithm, it can be guaranteed that water demand can be met sooner at areas where demand is highest. This implies that more consumers get to have their water supply back faster.

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