Joshimath: Manmade or Natural Disaster?

CS752 Course Project
by

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Contents

1 Problem Statement

Joshimath is a town in the Chamoli district of Uttarakhand state known for its scenic and geographic attributes; earlier known as a pilgrimage destination but now is a sinking town. The town has experienced significant land subsidence in recent years, resulting in infrastructure damage, property loss, and threats to human safety. The cause of the subsidence is not yet fully understood. Still, it is believed to be linked to the construction of hydroelectric power projects, the melting of glaciers due to climate change, and natural geological factors. We aim to find factors that led to this catastrophic change. Is it man-made or a natural calamity? How do these human-made effects in the area interact with climate change? What lessons will be learned from the incident while considering the future of the Himalayas? Could it have been avoided?

2 Objectives

- To develop a system dynamics model of the land subsidence phenomenon in Joshimath, which can simulate the complex interactions between different variables and identify key feedback loops and causal relationships.
- To identify the factors contributing to land subsidence in Joshimath and their relative importance, including natural geological factors, climate change, and human activities such as the construction of infrastructure.
- To assess the potential impacts of land subsidence on the local environment, economy, and community, including impacts on infrastructure, property, and human safety.
- To identify potential interventions to mitigate land subsidence and their effectiveness, such as reducing human activities that contribute to land subsidence, implementing land-use planning and regulation, and investing in infrastructure improvements.
- To conduct sensitivity analysis and scenario testing to evaluate the system dynamics model's robustness and the proposed interventions' effectiveness.

3 Introduction

Land subsidence is a geological phenomenon characterized by the gradual sinking or settling of the ground surface. This process is often caused by the compaction of underground soils and sediments, which results in a reduction of the pore space and an increase in the density of the material. Land subsidence can occur naturally due to geological processes such as the consolidation of sedimentary layers or the dissolution of underground minerals. Still, it can also be induced by human activities such as groundwater pumping, oil, and gas extraction, and the construction of buildings and infrastructure. Land subsidence 1 can significantly impact the environment, infrastructure, and communities. It can lead to the flooding of low-lying areas, the degradation of water quality, the collapse of buildings and infrastructure, and the loss of habitat and biodiversity. As such, it is a critical issue that requires careful monitoring and management to mitigate its effects. In Joshimath land subsidence may be caused because of the fragile ecosystem which may in turn be caused because of land sliding, deforestation, earthquakes and floods. Joshimath's land subsidence may also be contributed indirectly by tourism as it demands building better infrastructure which leads to road construction activity. In Joshimath there was also new infrastructure such as hydro-power plants and likewise there was use of blasts and dynamite to break or move the boulders and these boulders were the backbone of the land!

Poor drainage systems can lead to land subsidence through a process known as soil consolidation. When soil is saturated with water, it becomes heavier and exerts a greater pressure on the underlying

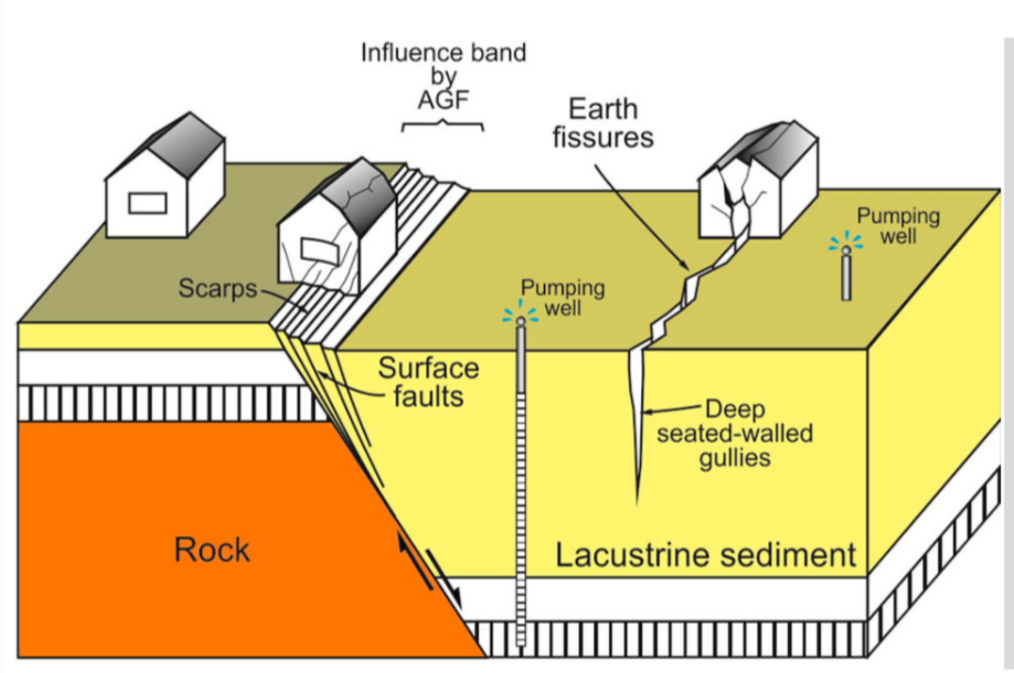

Figure 1: Process of land Subsidence

layers of rock or soil. If this pressure is not relieved by a proper drainage system, it can cause the underlying layers to compress and compact over time, leading to subsidence.

Here in this report, we will do a detailed case study analysis of land subsidence in Joshimath. The other section includes a background study of the land-sliding incident in Joshimath. In the methodology section, we will model land subsidence using a causal loop and stock-flow diagram, considering various factors related to the case study.

4 Background

Joshimath is prone to natural disasters such as landslides, due to its geology and topography. There have been many landslides in the Chamoli district, which resulted in widespread destruction and loss of life. The landslides are sometimes triggered by a glacial burst that occurred in the upper reaches of the Rishiganga river, which flows through the region. The landslide was caused by the force of the floodwaters carrying rocks, boulders, and sediment, which slammed into the mountain slopes, causing them to give way and slide downhill. The landslide resulted in the loss of several lives and caused significant damage to the infrastructure in the town.

The drainage system in Joshimath is also one of the leading causes for land subsidence. Sewer pipe breaches can result in simultaneous leakage of soil particles and groundwater into underground unoccupied spaces, leading to underground cavities and even surface earth collapse. The other main factors that are a worry are tourism which demands better infrastructure such as big buildings and the construction of better roads. These demands lead to use of blasts to move the boulders, which are the main component of this land. There are also other things such as floods and earthquakes, to be blamed on the list of natural causes.

On February 7, 2021, a massive landslide occurred in the Chamoli district, which resulted in widespread destruction and loss of life. The landslide was triggered by a glacial burst that occurred in the upper reaches of the Rishiganga river, which flows through the region. The glacial burst was caused by a massive avalanche of ice and snow that broke off from the Nanda Devi mountain range and fell into the river, causing a surge of water and debris to flow downstream. The wave of water and debris traveled downstream, causing significant damage to the infrastructure and settlements along the river's path. The wave reached the town of Joshimath and caused a landslide, which led to the

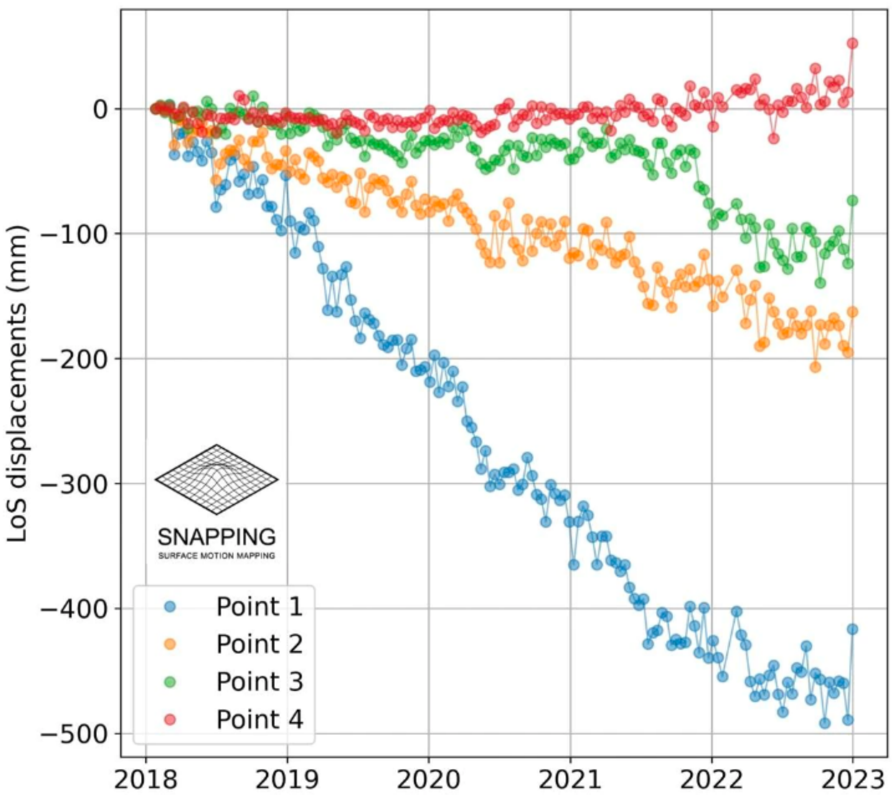

Figure 2: Land Displacement in Joshimath

destruction of several buildings, roads, and bridges in the area.

5 Literature Survey

As reported in the India today article by Sibu Tripathi, Joshimath, a place often exposed to earthquakes was supposed to be built with good infrastructure but despite 20000 people living and hub for the tourist, suffered from poor planning and foundational weakness. The boom in construction has made this region extremely vulnerable and susceptible to major land deformation.

In the Indian Express article "Cracks in Joshimath, cracks in policy: A warning against short-term profits", Anjal Prakash has reported that poor policies and neglecting ecology for short-term profits are at least partially to blame for the calamity that is currently unfolding.

As per Athira's report from The Wire, The construction of the Char Dham project – an ambitious 900 km-long all-weather road through the state to promote religious tourism – is also a cause, according to experts. In the report presented by Yaspal et al. (2023), slope stability simulation using continuum modeling was used to assess how these hill slopes will respond to loads such as gravity, rain, building loads, domestic discharge, and seismic loads. The displacement in 22 of these hill slopes may reach up to 20–25 m, according to the results, which will make the issue worse. The fact that these towns frequently experience high precipitation and that three significant earthquakes—i.e.,1 Sep. 1803 24 (Mw7.8), 20 Oct. 1991 (Mw 6.8), and 29 Mar. 1999 (Mw 6.6)—all had hypo-central distances of less than 30 km—make such a study more practical for making decisions. The town is a part of a hot-spot that is experiencing rapid anthropogenic influence and changing climate, according to a recent study by Agarwal et al. (2022). Upon closer inspection, it was discovered that the town's hillslope is made up of heavily jointed gneisses with schistose inter-layers rock mass, subsidence in the road, a broken retaining wall, holes, shifting boulders, and cracks in the homes. The eastern part of the town, with loose hillslope material exposed in the form of sandy-gravel soil (Fig. 1c), suggests a potential paleo-landslide where the majority of the town is situated. The most recent big earthquake (29 Mar,1999:

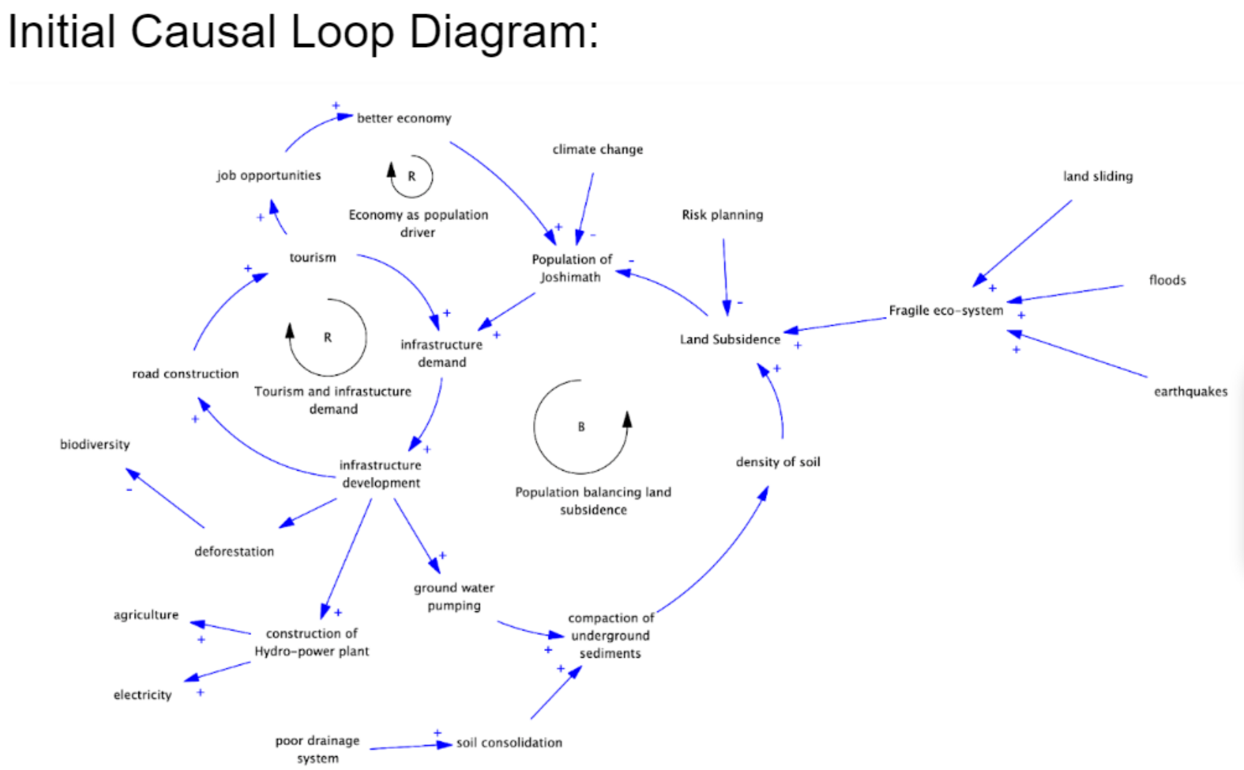

Figure 3: Initial CLD

Mw 6.6), happened 26 km hypocentral away from this town.4

Yadav et al. (2020) reported that between 2006 and 2016 at this location, material displacement ranged from 12 to 22 millimeters per year. The most recent large earthquakes, a Mw 7.8 earthquake on September 1, 1803 and a Mw 6.8 earthquake on October 20, 1991, both occurred 22 km hypo-centrally from this town.

6 Causal Loop Diagrams

In this section we will have two updates about the causal loop diagrams. One is the initial stage CLD then we upgrade this CLD to final bigger picture.

6.1 Initial Causal loop diagram

Fig 3 represents the initial causal loop diagram. Here we see 2 Reinforcing loops and 1 balancing loop. First Reinforcing loop is Economy as a population driver, and the second Reinforcing loop is Tourism and infrastructure demand. The Balancing loop is Population balancing land subsidence.

6.2 Final Causal Loop Diagram

Fig 4 represents the final causal loop diagram. It gives detailed overview of the Joshimath dyanamics. It covers various aspects affecting the joshimath land subsidence. There are 12 balancing and 4 reinforcing loops in the final CLD of Joshimath Disaster. The main amongst these are B1, B2, B3, B8, B10, R1 and R2. The main factors that we can say contributed to this disaster are Population and Tourism which has led to poor drainage, more groundwater pumping and infrastructure development. We also think that aquifer puncture has a big role in land subsidence at Joshimath, though many reports oppose aquifer puncture but after our enough research we are positive that it had a major contributing role as well. Many times we just try to classify the thing into just one category, but

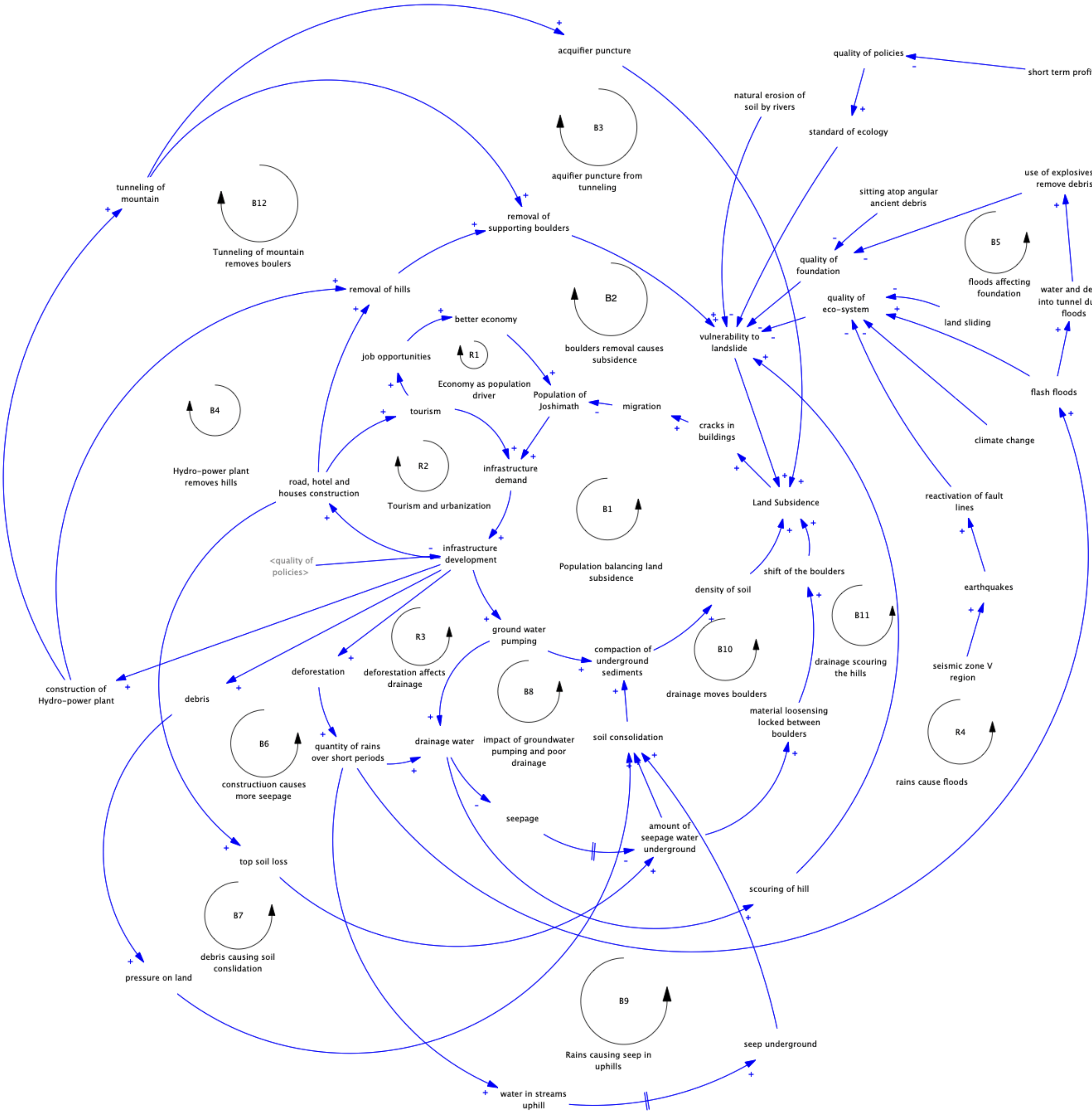

Figure 4: Final Causal Loop Diagram

our intuition turns out wrong and we find out that it was an amalgamation of both the things. So, it is not fully right to blame this disaster on only human factors, we have a saying in Hindi : "Sirf ek haath se taali nahi bajti". Here natural factors like floods have had a great contribution in the damage. The area has also been host for several earthquakes that take place in large numbers and over a large period of time this has put this holy site at risk of subsidizing.

Major feedback loops in the causal loop diagram :

6.2.1 Balancing Loops

- B1 : Population balancing land subsidence
  - As the population of Joshimath increases it leads to more infrastructure demand. More infrastructure demand leading to more infrastructure development. As the development increases then more groundwater pumping will be there. Groundwater pumping leads to compaction of underground sediments which eventually increases the soil density leading to land subsidence. As land subsidence happens there are cracks in the building which creates a fearful atmosphere among the people and people migrate out of fear so population reduces.
- B2 : Boulders removal causes subsidence
  - The infrastructure development leads to construction of roads, houses and hotels. As Joshimath is a hilly area, for construction there is a need of removal of these hilly areas. While removing the hills we also need to remove the supporting boulders which makes the system vulnerable to land subsidence causing the land subsidence.
- B3 : Aquifer puncture from tunneling
  - Tunneling activities are quite frequent near the areas of Joshimath. Tunneling is done for the construction of hydro-power plants. Tunneling causes aquifer puncture which makes Joshimath vulnerable to land subsidence.
- B4 : Hydro-power plant removes hills
  - For infrastructure development there are need of constructing hydro-power plant for various uses. But it requires removal hilly areas. We have seen that how removing hilly areas are affecting the land subsidence
- B5 : Tunneling mountain removers boulders
  - Tunneling of mountain occurs because of hydro-power plants and this tunneling has lead to the removal of the supporting boulders which are the foundation of Joshimath.
- B6 : Construction causes more seepage
  - Construction causes loss of top soil in the area. Loos ing topsoil leads to soil erosion. As the soil erosion increases the amount of seepage water also increases. Due to this the materials loose strength between the boulders. Which eventually leads to loosing boulders and causing land subsidence
- B7 : Debris causing soil consolidation
  - Again as there are more construction activities and infrastructure development there are debris formation due to such activities. This debris increases pressure on the land causing more soil consolidation. More soil consolidation leads to compaction of underground and lead to land subsidence as seen in loop B1.
- B8 : Impact of groundwater pumping and poor drainage

- It has been observed and stated in the reports that the drainage system has been a failure in Joshimath. The poor drainage system is due to the high underground pumping of the water. The poor drainage system causes more water seepage underground eventually leading to land subsidence.

- B9 : Rains causing seep in uphills
  - The infrastructure development leads to the deforestation which leads to unnatural rains. These rains increases the upstream water levels. The upstream water causes more seepage underground and rest dynamics is explained in other loops how it leads to land subsidence.
- B10 : Drainage moves boulders
  - As we have seen that drainage system has been a problem in Joshimath. B8 explained about how seepage leads to soil consolidation eventually leading to subsidence. The seepage underground water also makes the underground boulders to loosen their strength which shifts the underground boulders leading to land subsidence.
- B11 : Drainage scouring the hills
  - This loop explains how drainage affects souring of hills and making the place vulnerable to land subsidence. Poor drainage management leads to drainage water flowing over the hills, scouring them over time.
- B12 : Tunneling of mountain removes boulders
  - Tunneling activities are happening frequently in the which are leading to removal of supportive boulders making system vulnerable to land subsidence.

6.2.2 Reinforcing Loops

- R1: Economy as Population driver:
  - More tourism leads to better job opportunities which in turn leads to a stronger economy. Thus a stronger economy attracts immigrants who increase the population. This population puts demand on infrastructure which if better leads to more tourists.
- R2 : Tourism and urbanisation
  - More tourism leads to better economy which in turn strives to build a better infrastructure. This infrastructure is good enough to hold more tourists and thus tourists gets attracted to Joshimath.
- R3 : Deforestation affects drainage
  - Deforestation leads to change in rain patters such that heavy rains occur over a short period of time. This excess raining causes more load on drainage system as now more water is present in the drainage.
- R4 : Rains cause floods
  - As the rains over a short period of time are increasing this has led to increase in amount of flash floods. These floods are pretty damaging for the land and livelihood. These floods have led to the collection of debris in tunnels and also the quality of eco-system gets thus causing land subsidence.

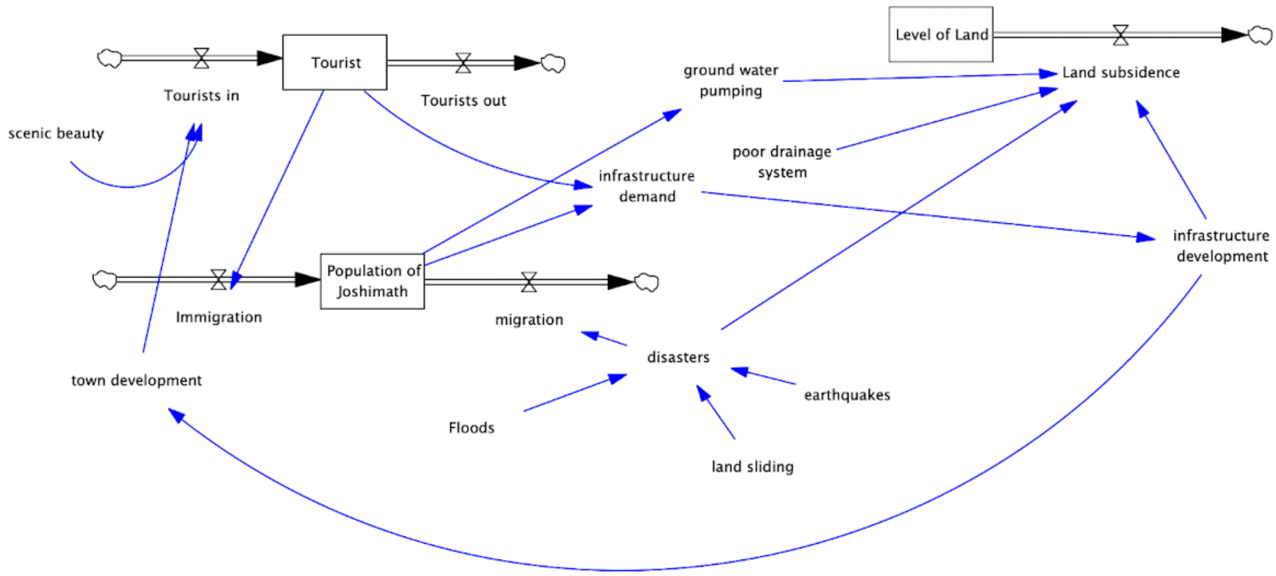

Figure 5: Initial Stock and flow diagram

7 Stock and Flow Diagram

In this section we will have overview of stock and flow diagram. We have started with some initial assumption and then make a big picture view of the SFD. Finally we simulated a small model to represent how population and infrastructure affects the land subsidence.

7.1 Initial SFD

We have taken 3 stocks such as Level of Land, Population of Joshimath and Tourists. Land subsidence is the output of a fragile ecosystem which is formed by natural factors such as floods, land sliding and earthquakes, in the category of Man-made factors there are Groundwater Pumping, Infrastructure Development and Poor Drainage System. Fig 5 represents the initial SFD.

7.2 Final SFD

Fig 6 Represents the final stock and flow diagram of the Joshimath dynamics. It has detailed analysis of how various stocks are affecting the dynamics. Various stocks in the diagram are

- Population
- Tourist
- Economy
- Ground water
- Water for use
- Drainage water
- Seepage water underground
- Infrastructure
- Amount of Debris

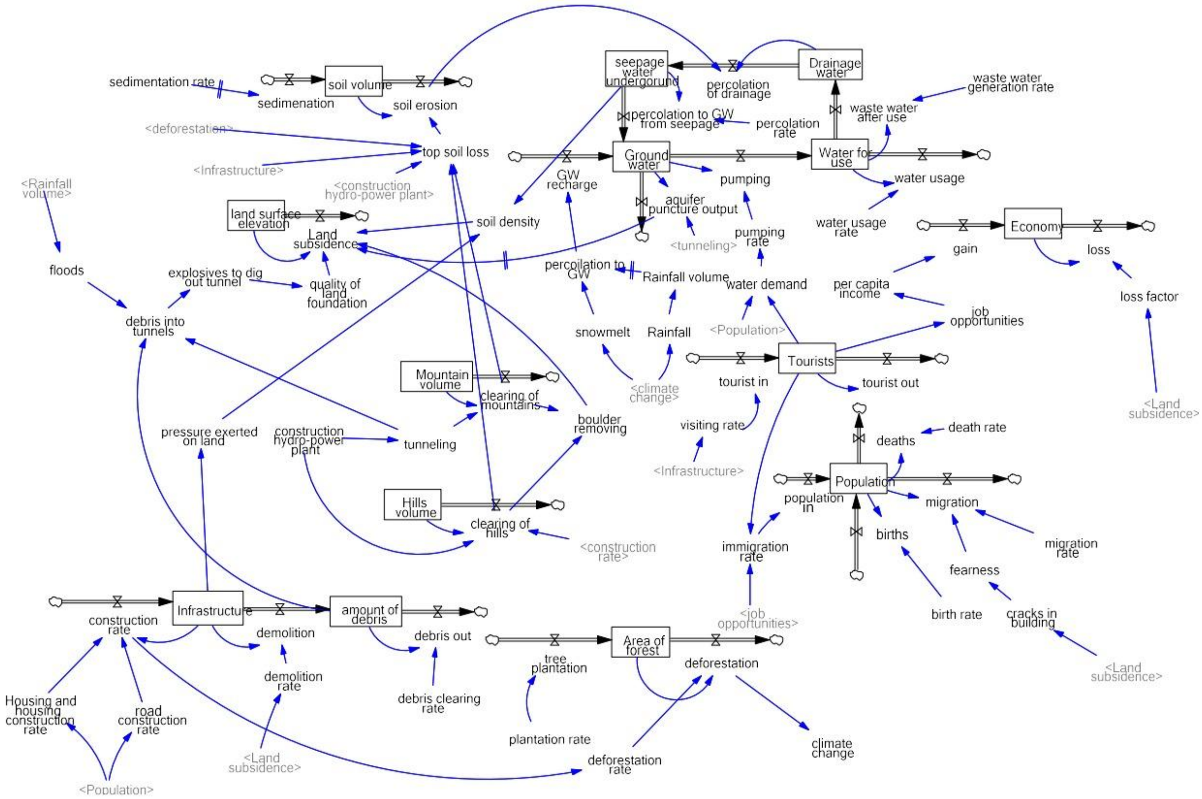

Figure 6: Final Stock And Flow Diagram

- Area of forest
- Mountain volume
- Hills Volume
- Land surface elevation
- Soil Volume

The detailed explanation of various components of SFD is given below

7.3 Population dynamics

Population is increased because of births and also because of immigration and it reduces due to deaths and out-migration. Migration is determined by the fear that people feel because of cracks in the building. Immigration rate is determined by the job opportunities which come into play because of the tourist population. Population also stresses on water demand along with the tourist population. This pumping of excess water causes soil density at bottom to grow thus reducing its volume and this pumped water is passed onto to drainage, which impacts the land subsidence.

7.4 Economy Dynamics

Economy is determined because of tourism. As tourists help build the number of job opportunities which increases per capita income and that is how economic gain occurs. Infrastructure determines the visiting rate of tourists and thus more infrastructure supports more tourists and this causes economic gain and this leads to even better infrastructure. So, it's a vicious circle.

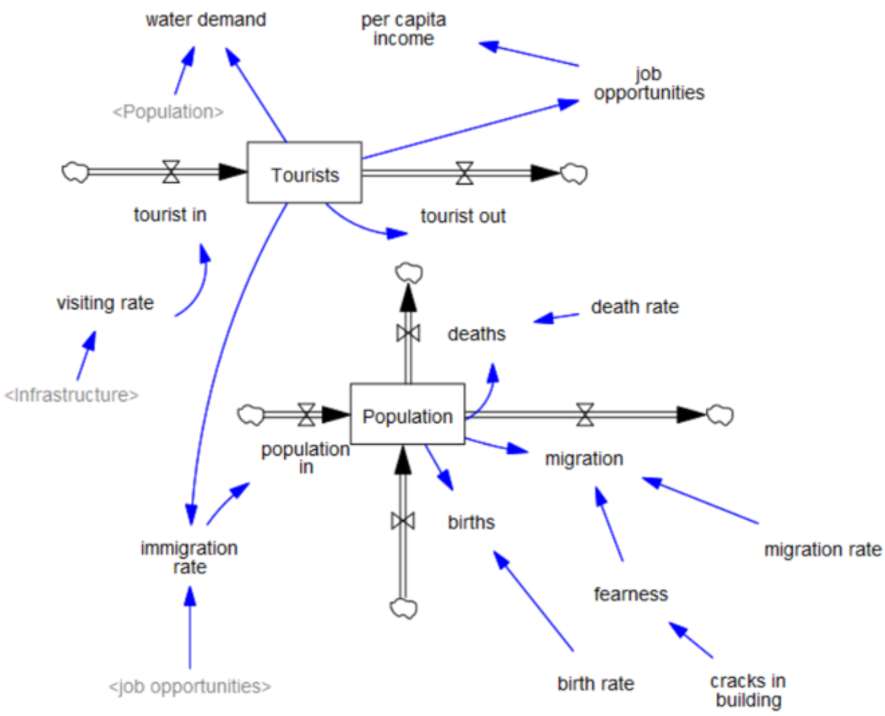

Figure 7: Population Dynamics

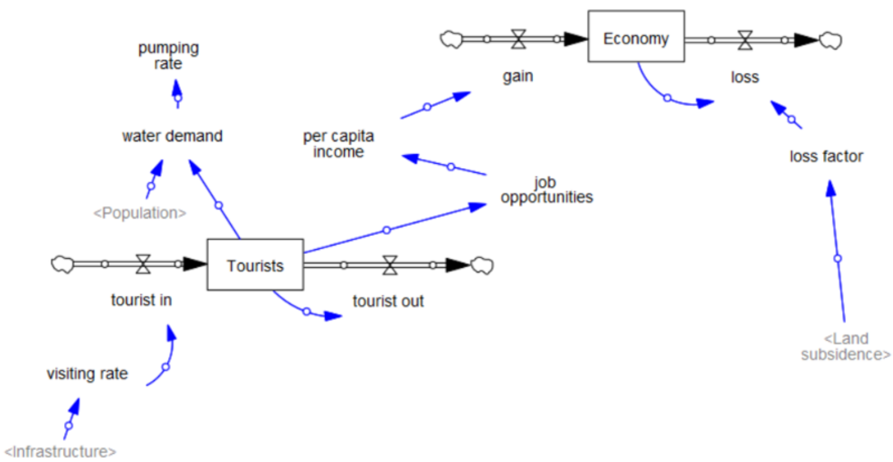

Figure 8: Tourist Economy Dynamics

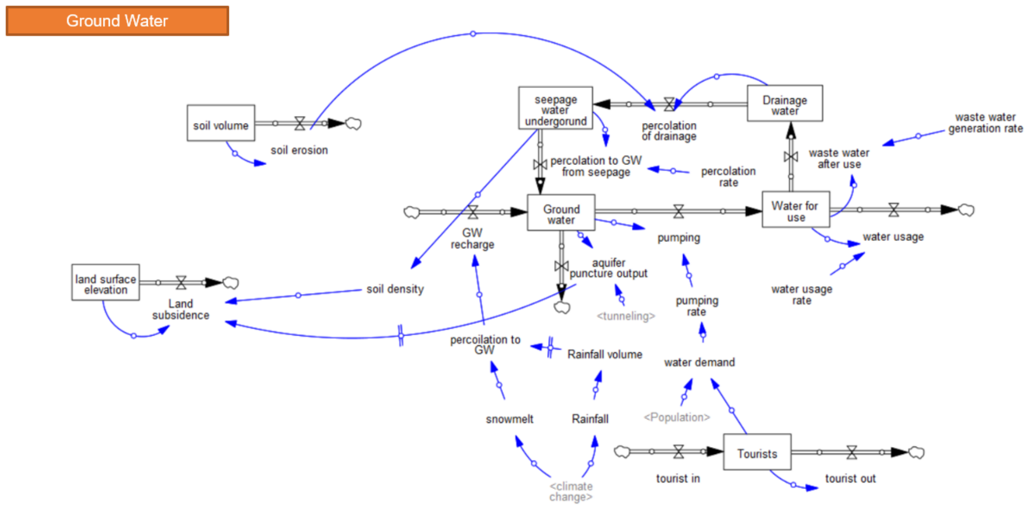

Figure 9: Ground Water Dynamics

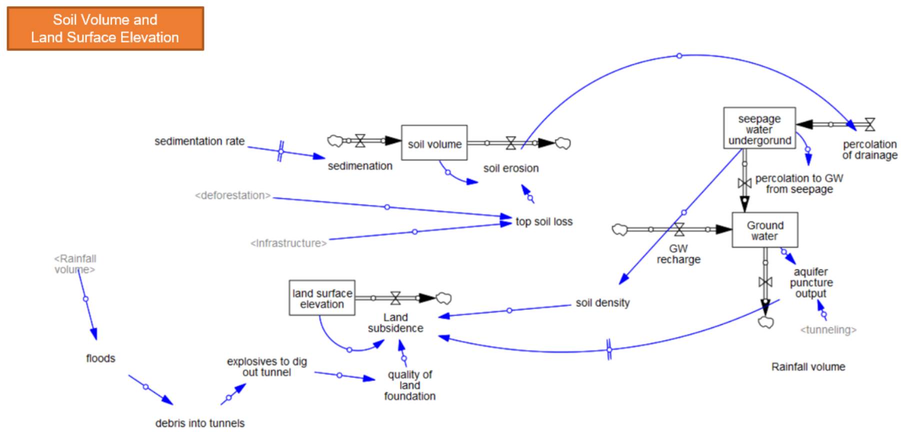

Figure 10: Soil volume and land surface elevation dynamics

7.5 Groundwater Pumping Dynamics

Fig 9 represents the ground water dynamics for land subsidence. Groundwater is also a contributing factor for land subsidence, it affects in several ways. First way is that the Groundwater gets pumped and becomes water for use which after use gets converted to Drainage water which percolates and gets converted into seepage water underground, this causes the soil density to grow and volume to reduce, which causes land subsidence. This seepage water also gets percolated to even down to get converted into Groundwater once more. Soil volume around the Joshimath area is decreasing because of various factors and this directly affects the percolation of drainage. As more soil erosion occurs, it is easier for the water to turn into seepage water underground. Groundwater recharge occurs due to rainfall, some amount of which gets percolated to ground. We also think that the land subsidence is being caused because of aquifer puncture which occurred during the tunneling of the hydro-power plant.

7.6 Soil volume and land surface elevation

Fig 10 represent how soil volume and land surface are interconnected and explains the dynamics of the system. Soil erosion occurs due to topsoil loss which occurs due to 2 main factors such as deforestation and infrastructure. Soil volume gets formed because of sedimentation. Rainfall causes floods which have introduced debris into the tunnel many-a-times and to dig out the debris explosives were used, which have affected the quality of land foundation in Joshimath and thus helping to land subsidence.

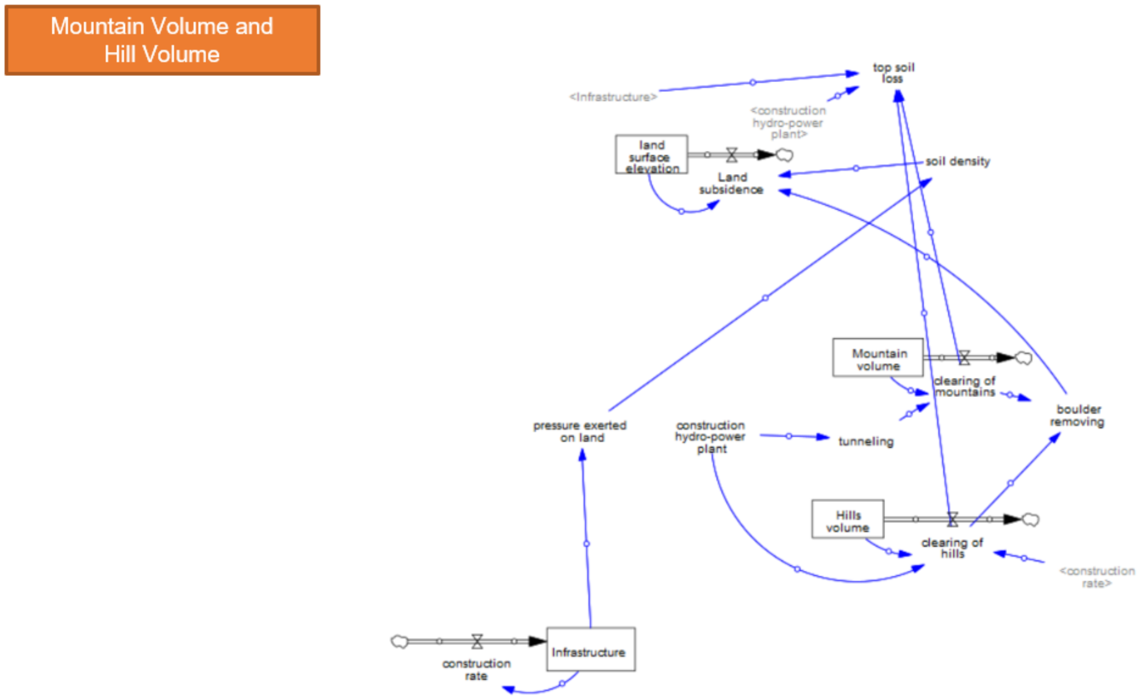

Figure 11: Mountain and hill dynamics

7.7 Mountain and hills Dynamics

Fig 11 represents the dynamics of the system about mountains and hills clearing affects the land subsidence. Construction of infrastructure is causing deforestation. If the plantation rate doesn't balance the deforestation rate then the forests will collapse and infrastructure will grow out more to clear the area. Infrastructure is affected by the road construction rate as well as hotel and house construction rate.

7.8 Infrastructure and area of forest

Fig 12 shows the dynamics of infrastructure and forest affecting land subsidence. Construction of infrastructure is causing deforestation. If the plantation rate doesn't balance the deforestation rate then the forests will collapse and infrastructure will grow out more to clear the area. Infrastructure is affected by the road construction rate as well as hotel and house construction rate.

8 General Analysis of the System

In this section we will run simulations of the SFD shown in fig. 13 for various parameters and try to understand the dynamics of the system.

8.1 Assumptions

- Initial Population of Joshimath = 25000
- The minimum land subsidence will be 8 cm per year.
- Birth rate is 16.42 people per every 1000 people per year
- Death rate is 9.42 people per every 1000 people per year
- Area of Joshimath is 4677 sq km

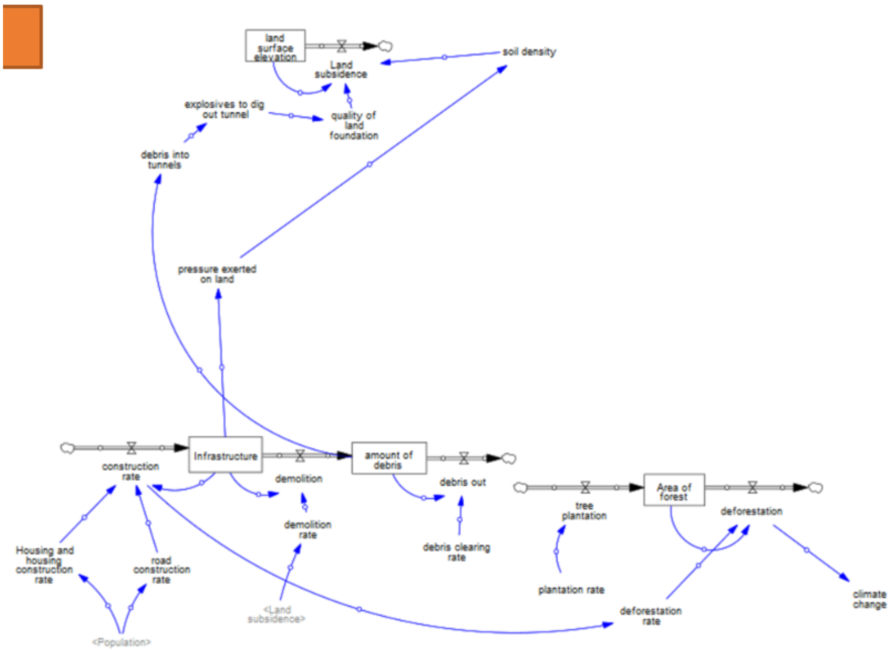

Figure 12: Infrastructure and Forest Dynamics

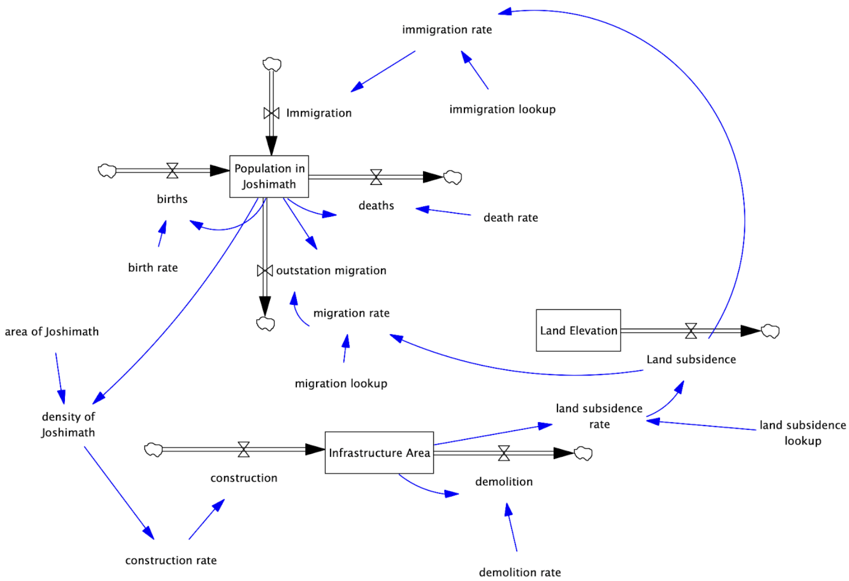

Figure 13: SFD Model for simulation

- Construction rate is dependent on density of Joshimath, we have taken it as density/10 sq km/year
- Initial value of Infrastructure Area is 100 sq km
- Demolition rate is 0.3
- Initial land elevation is 1875 m
- Minimum land subsidence is 8 cm/year and maximum is 30 cm/year and it is given by exponential lookup
- Migration rate is dependent on a linear lookup which has a minimum rate of 2
- Lookup for migration is dependent on the situation, we have considered it to be linear.
- Lookup for land subsidence:
  - {[(0,8)-(4677,30)],(0,8.07692),(438.171,8.84615),(1028.75,10.2308),(1657.43,11.6154), (2419.47,14.0769),(3105.3,17.0769),(3686.35,20.6154),(4219.78,24.3077),(4629.37,29.7692)] }
- Lookup for immigration:
  - {[(0,0)-(30,1000)],(0,1000),(0.977597,814.685),(2.50509,632.867),(4.21589,461.538),(5.37678,300.699), (7.08758,153.846),(10.1426,76.9231),(13.0143,48.951),(15.947,45.4545),(19.0631,27.972),(26.0285,0), (29.8167,3.49652),(30,20.979)]}

8.2 Formulas:

- Births = Population in Joshimath*birth rate (people/year)
- Deaths = death rate*Population in Joshimath (people/year)
- Immigration = immigration rate(people/year)
- Outstation Migration= Population in Joshimath*migration rate()
- Population of Joshimath= births+Immigration-deaths-outstation migration (people)
- Immigration rate=immigration lookup(Land subsidence*100) (people/year)
- Density of Joshimath= Population in Joshimath/area of Joshimath

We have analyzed that out-migration rate determines the collapse of the population of Joshimath. Thus for different settings we have different results. We will discuss the results that we think are worth.

9 Results

In this section we will analyze the results obtained from various simulations.

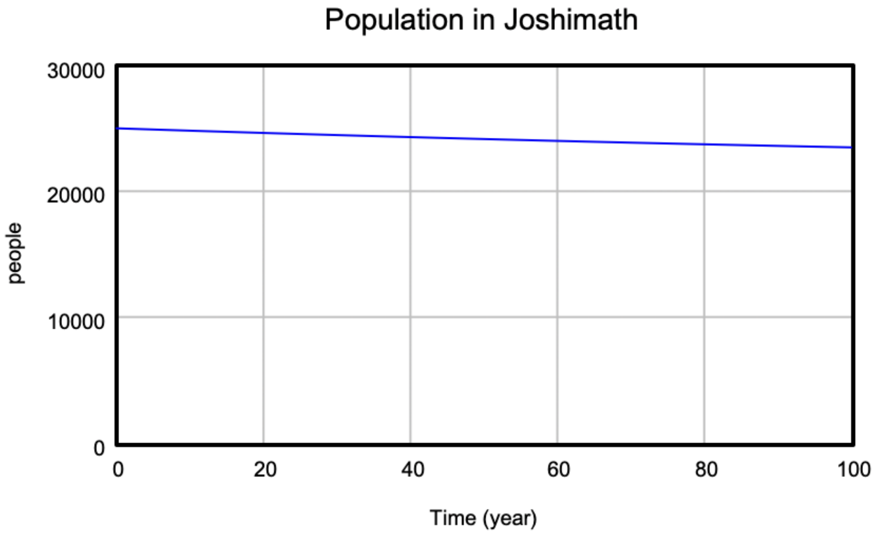

Figure 14: population graph

9.1 Population reduction due to land subsidence

If land subsidence occurs at a rate of at least 8 cm/yr and the people continue to move out at an average rate of around 1% to 2 % then it reduces from 25K to 23.5K after 100 years as per fig 14. Look up for out-migration is: [(0,0)-(30,0.02)],(0,0.01),(30,0.02)

- Infrastructure increases from 100 sq km to around 119 sq km as per fig 15.
- Land subsidence occurs at a rate of 8.25 cm/year in the 1st year and 8.28 cm/year in the 100th year as per fig 16 . So, we don't see any increase in land subsidence because of population reduction.
- Population is decreasing because of migration rate in between 1% and 2% but that doesn't stop infrastructure from being built up, infrastructure will continue to be constructed more that causes land subsidence to increase by 0.3 mm towards the end of 100th year. It's clear that even if population reduces infrastructure would continue to come into existence if demolition rate remains as low as 0.3%.

9.2 Population increases despite land subsidence

If land subsidence occurs at a rate of at least 8 cm/yr and the people continue to move out at an average rate of around 0.003 % then it increases from 25K to 50.3K after 100 years as per fig 17. We have used the lookup for migration as follows: [(0,0)-(30,0.02)],(0,0.001),(30,0.01)

- Infrastructure increases from 100 sq km to around 143 sq km as per fig 18.
- Land subsidence occurs at a rate of 8.25 cm/year in the 1st year and 8.32 cm/year in the 100th year as per 19. So, we don't see any increase in land subsidence because of population reduction.
- Population is increasing because of migration rate in between 0.1% and 1% and that builds the infrastructure even more, infrastructure will continue to be constructed more that causes land subsidence to increase by 7.2 mm towards the end of 100th year.

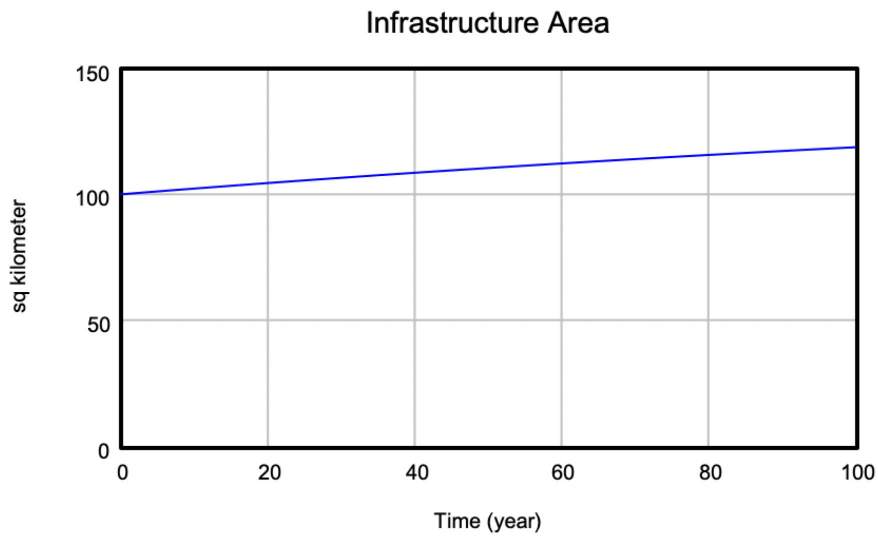

Figure 15: Infrastructure graph

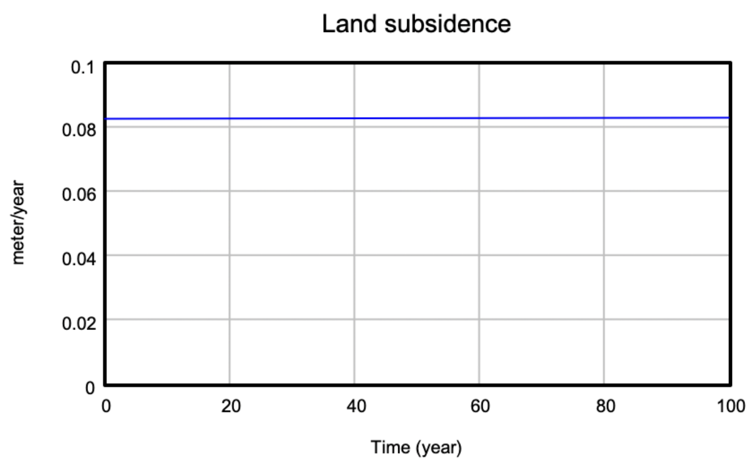

Figure 16: Land Subsidence Graph

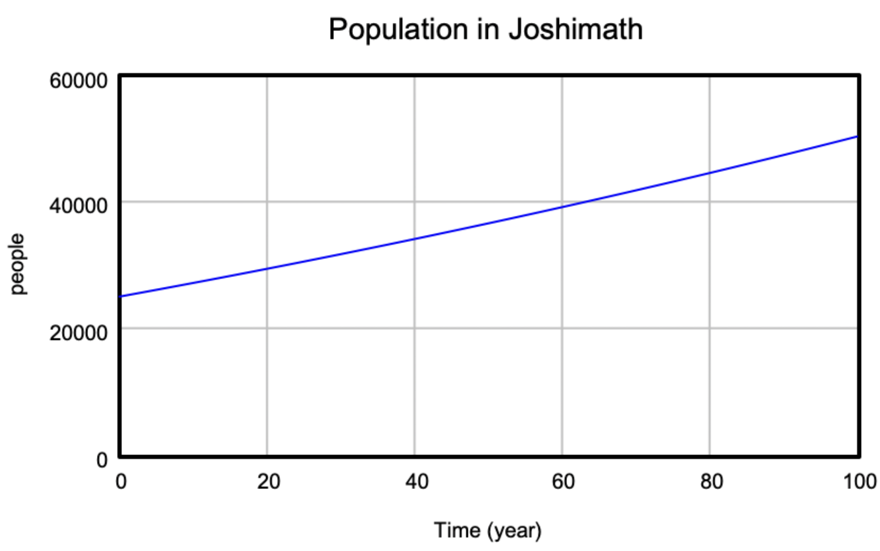

Figure 17: Population Graph

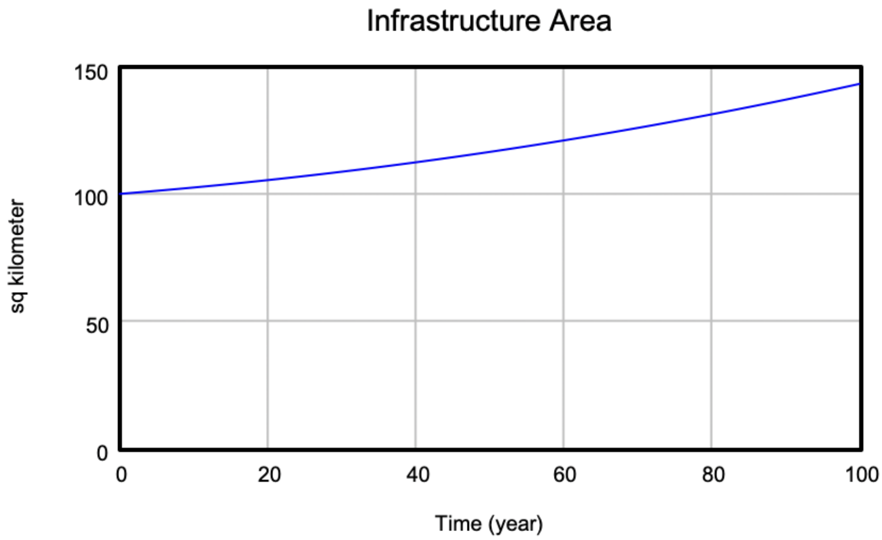

Figure 18: Infrastructure Graph

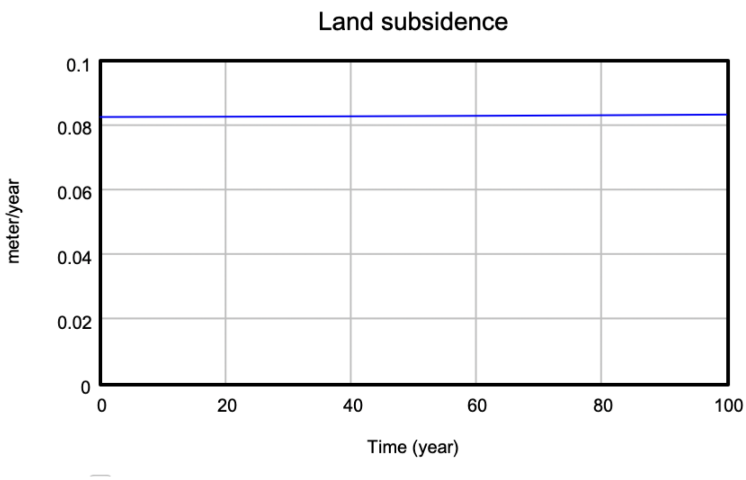

Figure 19: Land Subsidence Graph

10 Challenges

- Getting the stocks and flows right
- Too much information but not many facts
- Modeling Natural Disasters
- Modeling Government Policies
- Too many assumptions
- Getting the units right everywhere

11 Conclusion and Future Scope

- As per our research this disaster couldn't have been avoided, not even if all the man-made factors were eliminated, but it could have been delayed, and sometimes delay is all you need.
- Natural calamities had just as much contribution towards the damage of it as the man-made factors.
- Migration rate will determine the Population of Joshimath in future, if it continues at rate of 1 to 2 % then population will decrease
- Prevention is better than cure lesson learnt here
- For future this project can be further extended to work with the real data like by the relationship between infrastructure and land subsidence.
- More research can be done to find out the exact migration rate and various other assumed factors.

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