Transcript – Creation of hazard susceptibility maps in METEOR

4. This schematic provides an overview of the methodology- from the frequency ratio analysis through fuzzy membership functions, expert elicitation, map aggregation and the production of landslide susceptibility and hazard maps for both rainfall and earthquake triggered landslides. I'll go through the schematic and provide an overview of how each step was undertaken.

5. In our introduction to landslides we talked about how susceptibility maps are produced by analysing the pattern and distribution of landslides with a set of thematic data.

6. In the case of Nepal we had a number of thematic maps to assess against landslide distribution. The MERIT DEM, which was used across the whole METEOR project, was used to create a slope map and an aspect map. The MERIT DEM, a global DEM at 90m resolution, approximates elevation of bare ground by reducing vegetation height. It would have been advantageous to produce a slope curvature map but it was felt the resolution of the DTM was not sufficient. The geological map used was the Department of Mines and Geology 1:1Mil scale geological map of Nepal. We grouped together the formations to produce 6 classes of geological formations which were lithologically similar. The six classes comprised the recent geological formations such as Quaternary sand and gravel deposits, the Himal Group Gneisses, the Cretaceous sedimentary formations such as Eocene shales, a group of mixed lithologies which were typically bedded or foliated and susceptible to deep weathering, the limestones and quartzites and then the Mid Miocene and Pleistocene formations of the Siwaliks. We created these 6 classes because the spread of landslide data, if we were to use all of the separate geological formations, it would have meant only a few landslides in each formation, which would have given us less statistically significant results. We also took into account the distance to faults and lineaments to capture the effect of these on the geological materials. Geological material around faults have undergone shearing and can be weaker and more fractured which can influence slope stability. Drainage density was included in the analysis, derived from the ICIMOD river network, and is a measure of the length of stream channel per unit area of the basin. It has been positively correlated with landslide occurrence in a number of studies. Two separate landslide inventories were created to reflect the two different triggers being investigated. The rainfall induced landslide inventory was taken from the NASA global landslide catalogue whilst the earthquake triggered landslides came from a number of sources including ICIMOD and a USGS open source inventory on seismic induced landslides. The earthquake inventories contained a mix of polygons and point and these were combined to create one inventory of point data, ensuring no double counting took place. The 18,500 earthquake triggered landslides were largely concentrated in the area affected by the Gorkha earthquake whilst the 359 rainfall induced landslide points were more uniformly distributed across Nepal. For the rainfall induced landslide susceptibility map Annual Mean Rainfall was included, taken from rainfall records recorded monthly at 166 weather stations across Nepal between 1976 and 2005. Land Cover was included in both the earthquake and rainfall triggered landslide susceptibility map and utilised the 2010 land cover map of Nepal which had 8 classes.

Prior to carrying out any analysis the factor maps were rasterised at a 90 m grid cell resolution and all distance-related predictors were buffered in ArcMap 10.3.1. The 90m resolution applied was to bring the different layers in line with the DTM resolution.

7 Frequency ratio- In this section of the presentation I will discuss how we used the frequency Ratio method to eliminate those predictors that do not show any relationship with

landslide occurrence, assess the prevalence of landslides within a specific predictor class, and using that define rule sets and parameters (threshold values) for the fuzzy inference.

I will start with a brief overview of FR and then move onto how we produced and interpreted the results.

8. Frequency ratio can be defined as "*the ratio of the probabilities of a landslide occurrence to a non-occurrence for a given attribute*" (Lee and Talib, 2005). Frequency ratio is a quantitative, bivariate statistical method that is relatively straightforward to implement in GIS and there are a wealth of studies published in the literature using this methodology. The frequency ratio is the ratio of the area where landslides occurred in the total study area, and also, is the ratio of the probabilities of a landslide occurrence to a non-occurrence for a given attribute. Area ratios for landslide occurrence and non-occurrence are calculated for each factor, and the area ratio for factor to the total area is calculated. Finally, the frequency ratios for each range or type of factor were calculated by dividing the landslide-occurrence ratio by the area ratio.

$$FR_i = = \frac{PL_i}{PF_i}$$

$$\frac{the\ frequency\ of\ landslides \in the\ F_i\ area}{the\ frequency\ of\ the\ F_i\ area}$$

$$= \frac{the\ area\ of\ landslides \in the\ F_i \div the\ area\ of\ landslides \in the\ study\ area}{the\ area\ of\ the\ F_i\ area \div the\ area\ of\ the\ study\ area}$$

A final landslide susceptibility map is created by summing all of the FR results for each factor map in every pixel. In this study as well as eliminating any factors that were not relevant we used the FR results to inform the creation of fuzzy rule sets.

9. The processing of the FR took place utilising Arc GIS and excel. This is a segment of our results for both the rainfall and earthquake induced landslides –the higher the ratio the stronger the relationship is between the conditioning factor and the occurrence of landslides. If this ratio is greater than 1, it indicates a strong relationship between the occurrence of landslides and the factor's class, if the ratio is less than 1, then the relationship between landslide occurrence and the factor class is weak. A value of 1 is an average correlation. Once we had the results we carried out a sense checking exercise to determine if these figures made sense- utilising literature and our collective experience of landslide processes. If we take slope as an example different results were obtained for rainfall triggered landslides compared to earthquake triggered landslides. In the rainfall triggered landslides the slope angles which showed the highest FR, and therefore stronger relationship between landslide occurrence, were the slopes at 15- 35 degrees. Slopes ranging between 15-20 degrees had the highest frequency ratio at 1.35 whilst those slopes between 20- 35 degrees had a Frequency ratio of 1.22. Rainfall triggered landslides such as shallow translational debris slides can be triggered by rainfall on these more moderate slopes. Debrs flows, another type of landslide often triggered by intense rainfll are generally initiated on slopes over 25 degrees but tail off after 50 degrees. We have seen studies from across Nepal where landslides are triggered at these slope angles and failures at the lower end of this range may reflect movement in material that has previously failed. Case studies in the literature also suggest that post earthquake rainfall induced landslides can occur at lower slope angles, especially if they are taking place in landslide deposits, loose debris and colluvium previously weakened by the earthquake. Landslides triggered by heavy rainfall post the

Wenchaun earthquake in 2008 were shown to have occurred on lower slope angles than previously at between 20-40 degrees. For EQ triggered landslides the highest frequency ratio figures in our study were in slopes over 35 degrees. Slopes of 35-35 received a FR of 2.65 whilst a figure of 3.05 for slopes was determined for slopes over >45 degrees. When we looked at statistics from studies carried out on landsldies triggered by the Gorkha and Wenchuan EQ the peak of landslide density was at 40-50 degrees and 50-60 degrees respectively and the peak frequency of landslides event associated with the Gorkha event was around 40 degrees. In the literature the occurrence of earthquake-induced landslides on steep slopes has been attributed to topographic amplification of ground motions and reduced external loads required to trigger landslides on steep slopes.

For aspect there showed a small amount of divergence for the two different triggers- for Rainfall triggered landslides slopes facing SE through to W showed the strongest relationship to occurrence of landslides– possibly reflecting the prevailing direction of the monsoon rains, whilst the earthquake triggered landslides were clustered more from the E to the SW. Both sets of data indicated that North facing slopes were less susceptible to landslides.

10. Next we will move onto the fuzzy logic section- explaining briefly what that is, the creation of fuzzy rule sets and fuzzy membership functions. I will add useful references to the end of the presentation.

11. Spatial objects on a map are considered members of a set, and fuzzy logic utilises sets without defining a crisp boundary. In classical set theory a value of 0 or 1 is assigned whilst in fuzzy set theory a value can be assigned between 0 and 1 to show the varying degrees of membership values of the elements within a set. For instance a slope angle class will be assigned a number between 0 (not susceptible) and 1 (susceptible) which is representative of the degree of membership that the class has in the fuzzy set. These values can be user defined or defined using a technique such as frequency ratio or AHP.

Fuzzy logic allows you to deal with subjective uncertainty- boundaries of classes don't have to be a single figure- so for instance in the last slide we looked at slope angle. Realistically the slope angle threshold for landslides to occur is unlikely to be a single figure- using a fuzzy set allows you to assign a value between 0-1 for slope angle classes allowing more of a fuzzy boundary of increasing likelihood of landslide related to slope. So whilst we might assign 40 degrees as being our peak slope angle for landslides that doesn't mean that 38 has to be not susceptible as in reality it is unlikely the boundaries are this sharp.

12. Lets have a look at a simple example of fuzzy set theory and how we use membership functions to assign a membership value between 0-1.

If we consider height- in classic theory person B would be tall and person A would not be tall. However whilst this logic works a person, represented by the red arrow, would also not be considered tall and would be in the same category as person A despite their closeness in height to person B.

If we utilise a fuzzy membership function person B is still tall (value of 0.95) whilst person A is still not tall (0.3). However our person with the height at the red arrow, is now valued around 0.7 showing how they are likely to be considered more tall than short.

13. We used the FR and expert elicitation results (covered in the following slides) to define rule sets for each factor map. For instance a rule set for slope might be that susceptibility is at a maximum between 15 and 35, but as slope reduces below 15 and increases above 35 the susceptibility reduces at differing rates. This rule set is then defined quantitatively by the

membership function, which associates an input value to its appropriate membership value. We used three different functions for our continuous data- Bell, Z and S shaped and the selection of the appropriate function was guided by the results of the FR assessment and expert judgement- Bell shaped curves were utilised for variables with a normal distribution whilst S and Z shaped curves were used when the factor had a threshold at which the susceptibility reached a maximum value. For instance a z shape curve, where values are high and then drop off after a certain point, was used to define membership values for distance from faults. An S shaped curve was utilised when the factors values increased to a point and then remained high- in this case we used S shaped curves for annual mean rainfall as well as slope angle for earthquake triggered landslides. A similar function cannot be applied to categorical data and weights were assigned and implemented directly in the creation of the geology map without using a membership function. More detail on the creation of the rule sets and fuzzy logic membership functions is covered in the following presentation on the implementation of the methodology in GIS.

14. The next stage of the process was expert elicitation. In this stage we utilised a range of experts in Nepal to gather local expertise to refine and inform our statistical analysis and rank our predisposing factors.

15. Expert elicitation is the process of obtaining probabilistic belief statements from experts about unknown quantities or parameters. It's not often you have all the data you need to make a decision or create a model so elicitation allows you to, in a structure way, produce a census of opinions from a group of experts- although you can see there are other reasons for using elicitation. We adopted this approach to ensure that out statistical assessment matches the shared expertise of in country exerts and to counter inherent bias and uncertainty in the analysis. It's important to capture a range of experts to account for experience and background but these are combined to allow for the creation of a single probability distribution for a parameter.

16. Using the Cooke Classical Method our aim was to generate a weighted average (across multiple experts) of subjective probability distributions for values of interest. This process takes place through 3 steps: Measuring accuracy, informativeness and weighting.

The first set of questions asked are calibration or target questions which have 'known' answers and allow the accuracy and experts understanding of their uncertainty to be assessed. These calibration questions should not be general knowledge type questions- such as what is the population of a certain city as it is unlikely that experts and non-experts would performs sufficiently differently in this type of question. It is also not possible, using these types of questions, to assess the expert's performance on the questions you will subsequently ask on the specialist subject of interest.

In order to measuring statistical accuracy each expert quantifies his/her uncertainty for each calibration question and variable of interest. By providing values for specific percentiles, each expert provides a statistical hypothesis.

To be able to measuring informativeness the classical model assigns each expert an information score, which is based on the density of the expert's assessments relative to a background distribution. Among statistically accurate assessments, narrower informative assessments are more useful than wide, uninformative assessments. Weighting – which we'll come back to but involves combining the experts accuracy and information scores.

17. Lets look at the spread of answers given by expert A across 10 questions. You can see the **fifth and ninety-fifth percentiles (light blue) which create a ninety percent credible range**—the expert believes there is a ninety percent chance that the true value falls between

those bounds. The dark blue is our median value- where the expert believes its just as likely the answer could be above or below that value. The red cross is our known value for our calibration questions. By providing values for specific percentiles, each expert provides a statistical hypothesis. Assessing the calibration questions we can observe how frequently the true values fall in the expert's different interquartile intervals. This provides a mechanism for validation.

18- Let's look at the accuracy and information value of the experts answers. Expert A is most accurate on questions 1, 2, 7, 8, 9 and 10 where the answers given fall within the 90% bounds. Q9 provides a well calibrated answer as the range of values given cover a narrow range and the answer is correct. Q1 gives low information value – whilst the expert is correct the range is so large that the answer is not precise enough. Q3 shows the importance of having both high accuracy and high information value. The answer is poorly calibrated as even though the bounds are small the answer is not within these limits showing the expert didn't understand the uncertainty with which they had answered the question.

19. Weighting - Statistical accuracy and information scores are multiplied to create an expert's combined score. Combined scores serve as the mechanism for producing performance-based weights for combining the experts' assessments. A combination of expert assessments is called a **decision maker (DM)**. The calibration statistical accuracy score varies more than then information score → *it drives the differences in weightings much more than the information score.*

20 Aggregation- This phase of the methodology involves combining our individual factor maps that have previously been assigned fuzzy membership values reflecting the frequency ratio analysis and expert judgement. The way you combine the individual factor maps into a final map will make a difference to your overall result as I will demonstrate on the next slide.

21. As you can see from these two sample maps the way the layers are combined makes a difference to the end result. For instance the first map uses arithmetic mean to combine the thematic maps and all factors are weighted equally. In the second layer slope and geology are multiplied to weight them more highly and aspect is then added. You can see that the two maps are very different and care should be taken when choosing a methodology to combine the maps, which can be an iterative process. In the frequency ratio and Weights of Evidence method for example the factor maps are summed together to create a susceptibility map that is a product of all of the underlying thematic variables. Other methods such as weighted overlay method or weighted linear combination involve reclassifying and standardising values and applying weight to factors and classes before combining the layers.

22. In this study we followed the methodology of Ruff and Czurda in order to combine the expert elicited results on importance of each factor map along with the results of the FR. The factors maps for both susceptibility maps were grouped into morphology, geology and environmental factors. Each factor within a group received a weight (W2), the total of the weights within each group was equal to 1. Then each group received a weight (w3), with the total of the group weights being equal to 1. W2 and W3 were multiplied by the value produced by the fuzzy logic maps and this gave the overall score of that cell for that factor. All of the factors maps were summed to produce the final susceptibility map value at that pixel. As in the frequency ratio we had one set of weights for the rainfall induced landslides and one set of weights for the earthquake triggered landslides. The final susceptibility maps was then classified into five different categories- very low, low, medium, high, very high susceptibility.

23 and 24- Susceptibility maps. An ongoing part of the work will be to validate these susceptibility maps when new data is available. Validation of susceptibility maps is an important step in the process and there are a number of techniques that can be used to assess the fit of the map. Techniques such as contingency tables can be used to compare the observed and the predicted results and can give a statistical measure of the quality of the map. Success rate curves can be generated to compare the susceptibility map with the training set whilst prediction rate curves utilise a separate dataset not used in the creation of the map. Other authors favour the creation of ROC curves where the Area Under the ROC Curve (AUC) can be used as a metric to assess the overall quality and predictive ability of the model.

25- This part of the presentation will show how the susceptibility maps were combined with maps representing the different triggers in order to create landslide hazard maps.

26. Reichenbach *et al.,* (2018) define hazard as "*the probability that a landslide of a given magnitude will occur in a given period and in a given area*". So, whilst susceptibility represents the spatial probability of landslide occurrence, hazard represents the temporal probability of a landslide (of a given magnitude) occurring. Hazard in this study is expressed through the combination of susceptibility and a trigger value following Varnes (1984) and is similar in approach to assessments carried out by Jaedicke *et al.*, (2014) and Nadim *et al.*, (2006). Susceptibility values are multiplied by a triggering factor to derive national scale maps depicting the hazard arising from both earthquake and rainfall triggered landslides.

27. 24 hr extreme rainfall data was used as the trigger factor for the rainfall induced landslide hazard map. Data comprised extreme rainfall values (mm/day) recorded monthly at 166 weather stations across Nepal between 1976 and 2005. A range of return periods were produced and the 1 in 50 year return period rainfall event was chosen for this study. Other return periods in the report (2, 5, 10, 15, 20, 25, and 100 years) could be used to produce different hazard probability maps. The final hazard maps categorise the terrain into five zones that are representative of the landslide hazard given a defined rainfall or earthquake scenario. The five categories of hazard, defined using a natural breaks method (Jenks, 1967), are: (1) very low; (2) low; (3) moderate; (4) high; and (5) very high.

28. Seismic trigger data comprising PGA data was supplied by GEM and developed by NSET using a standard Probabilistic Seismic Hazard Assessment approach (Stevens *et al.,* 2018). The seismic trigger data has a 0.1 probability of exceedance in 50 years (return period of 475 year) reflecting the standard design life of buildings. The PGA values derived from the GEM/NSET data were categorised into 12 classes following Jaedicke *et al.,* (2014) with an additional number of classes to reflect the higher PGA values in Nepal. The final hazard maps categorise the terrain into five zones that are representative of the landslide hazard given a defined rainfall or earthquake scenario. The five categories of hazard were applied in the same way as the rainfall hazard map (5 classes).

29. Final landslide hazard maps

30-31- Key references