Seven Years of Landslide Forecasting in Norway—Strengths and Limitations

Graziella Devoli, Hervé Colleuille, Monica Sund, and Jaran Wasrud

Abstract

The experiences acquired by the Norwegian Landslide Forecasting and Warning Service during the first 7 years of operation are herein presented. We summarize the warnings sent in the period 2013–2019 and we present the evaluation of the warning performance and discuss some of the main strengths and limitations of the service. In our opinion, of imperative importance to the success is: A national political will, the assignation of the landslide service to an existing well consolidated flood warning service and a strong collaboration across public agencies and a multidisciplinary approach. The existence of a national landslide database and of an operational distributed hydrological model, was essential for the rapid establishment of relationships between landslides events and hydro-meteorological conditions. A strong development of IT-tools and expansion of the meteorological and hydrological network was also crucial. Yet there are still several challenges and limitations, such as an insufficient process-understanding of rainfall- and snowmelt-induced landslides. The verification of landslide occurrence is also a difficult and tedious task. Finally, another challenging task is the prediction of landslides triggered by local intense rainshowers during summer, and rapid snowmelt events during winter, due to the limitations that exist in the models and thresholds currently in use.

Keywords

Rainfall- and snowmelt-induced landslides • Forecasting and warning services • Early warning systems • Debris avalanches • Debris flows

Introduction

Early warning systems are useful mitigation options for the authorities in charge of risk management and governance. With warning messages, the authorities should invite people to implement emergency plans, take local actions and trigger contingency and emergency management in order to reduce risk of life and damages.

For an effective and successful early warning system, many efforts from the different sectors of the society are required at different steps. Politicians may have interest in establishing such of systems to prevent landslides. Researchers need to assess landslide hazard and risk, and design warning models. Forecasters have to run forecasting and warning services issuing messages, when the landslide danger increases. Finally, local authorities and population must take actions and implement emergency plans upon receipt of warning messages. Coordination and cooperation among the different sectors are essential.

The organization and the maintenance of a Landslide Early Warning Systems (LEWS) is complex and require many key components and steps, as recognized by other authors (UNISDR 2006; Di Biagio and Kjekstad 2007; Intrieri et al. 2013; Calvello 2017; Fathani et al 2016; Piciullo et al. 2018).

Two types of LEWS are found worldwide: the one that address the prevention of single landslides at slope scale, also called *local*, and the others that covers a large area predicting the occurrence of multiple landslide at regional scale, called *territorial/regional* (Piciullo et al. 2018; Pecoraro et al. 2018). The majority of the regional LEWS were established

G. Devoli (✉) · H. Colleuille · M. Sund · J. Wasrud
Norwegian Water Resources and Energy Directorate, Middelthuns gate 29, Oslo, 0368, Norway
e-mail: gde@nve.no

H. Colleuille
e-mail: hec@nve.no

M. Sund
e-mail: mosu@nve.no

J. Wasrud
e-mail: jaw@nve.no

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after 2005 and are managed often by governmental institutions. They cover regions in South-East Asia, USA, Europe and South America.

The Norwegian Landslide Forecasting and Warning Service (known as "Jordskredvarslingen" in Norwegian), has been operational since 2013 and is described in Krøgli et al. (2018) and Devoli et al. (2018). It is managed by a governmental institution, the Norwegian Water Resources and Energy Directorate (NVE), to forecast the level of danger of rainfall- and snowmelt-induced landslides, specifically shallow soil slides, debris avalanches, debris flows and slushflows (herein referred to as landslides). The service is operative 24/7 and covers the entire country. The daily management covers: the forecasters assessment of the danger level with a bulletin twice a day at www.varsom.no, improvements of organizational tasks, models, and public information. The main goal of the service is to issue correct warning levels at regional scale which trigger actions and implement emergency plans. Four awareness levels are used: green, yellow, orange and red (see Krøgli et al. 2018 for more details).

To maintain a system operational over a long time, periodic evaluations are mandatory to identify strengths or to detect problems in the system, and then propose changes and improvements (Segoni et al. 2018).

In this analysis, we aim to summarize the experience acquired between 2013 and 2019 and to evaluate some of the work done. We discuss how local and regional authorities react to warnings and how their response has changed through the years. Our experience can benefit the start-up of a similar service in other countries.

Warnings, Landslides and Warning Performance (2013–2019)

Norway is predominantly a mountainous country, with high relief and steep topography, product of repeated glaciations. Because of its elongated shape the country is exposed to a varied climate all year around. The complex geological conditions make the country also prone to different types of landslides (mainly rock falls, rock avalanches, rock slides, debris flows, debris slides, debris avalanches, clays slides and quick clay slides) but also slushflows and snow avalanches. The country is divided in 5 major physiographic regions: Northern Norway (divided in this work in two sectors Nordland and Troms/Finnmark), Central Norway (Trøndelag), Western Norway (Vestlandet), Southern Norway (Sørlandet) and South-Eastern Norway (Østlandet).

Warnings issued in the period 2013–2019

The number of days with landslide warnings varies from a minimum of about 25 days in 2016, to a maximum of 66 days, in 2013 (Fig. 1).

The figure shows all warnings sent for the different physiographic and climatic regions in Norway (from those with an annual rainfall amount of 200–300 mm to regions with rainfall amount of 3000–4000 mm). The figure do not differentiate the warnings based on the different triggering conditions. Some of these warnings were sent when high amount of rainfall episodes were forecasted, while other were sent because of snowmelt episodes or because of a combination of both. High soil moisture condition previous weather events was also an important variable in some of these cases. The fluctuations in number of warnings is due to daily fluctuation of both rainfall and snowmelt patterns in the different regions each year. In some years we sent clearly more warnings on springs as in 2013 and 2018 because these years had more snow than normal in South-East Norway and experienced fast snow melt.

On average, the yellow level is issued 40 days/year, orange 4 days/year, and red level 0,1 day/year.

Landslide warnings have been sent all year around in all regions. The average number of warnings per season is rather similar: 9 days, in summer, 10 in winter, 11 in autumn and 13 in spring (Fig. 2).

The number of days with landslides warnings during summer may be lower the last 4 years, since we have started to better differentiate the warnings sent for those days when convective clouds were expected. Convective clouds are responsible of short duration, and mostly intense rainfall, across localized areas, especially on summer (called herein heavy rainshowers). It is MET-Norway, in agreement with

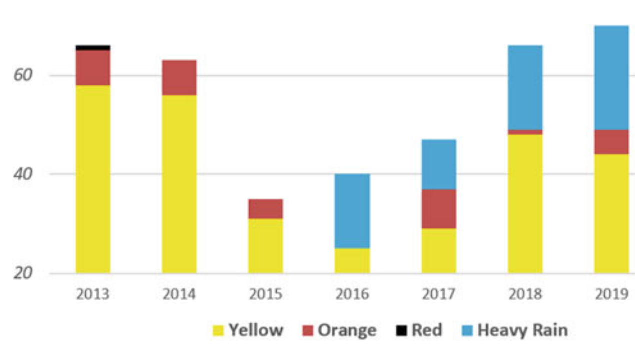

Fig. 1 Number of days with warnings issued in the period 2013–2019 with their respective warning levels, and number of days with warnings for heavy rain showers on summer (issued by MET-Norway)

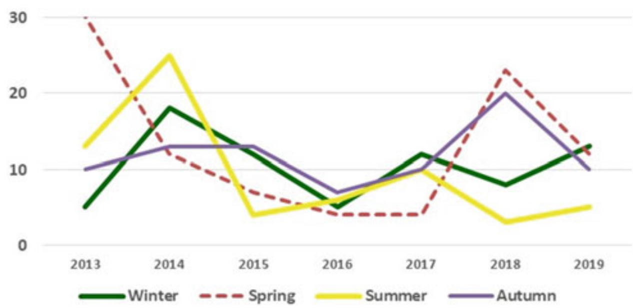

Fig. 2 Number of days with warnings by seasons in the period 2013–2019. The winter season is from December to February, week 49 to week 9, Spring from Mars to May, week 10 to 22, Summer from June to August, week 23–35, Autumn from September to November, week 36–48

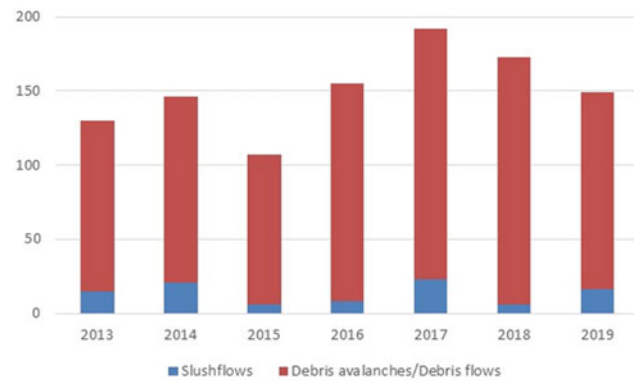

Fig. 4 Yearly distribution of landslides, from the verified dataset that forms the basis for the evaluation of the warning performance

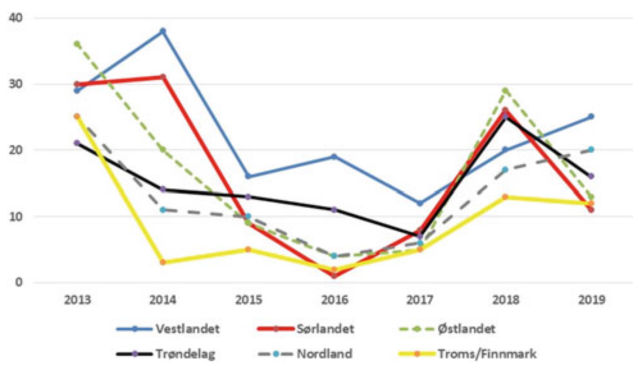

Fig. 3 Number of days with warnings divided by regions in the period 2013–2019

NVE, that issues warnings for heavy rainshowers. These warnings (indicated with a blue colour in Fig. 1) highlight the risk of surface runoff, storm water in urban areas, local flooding, local flash floods with erosional damage, debris flows and debris avalanches at locations impacted by the heavy showers.

Most of the warnings were issued in Western Norway (Vestlandet) (22 days in average) (Fig. 3), while the region that in average received the least landslide warnings (9 days) was Troms/Finnmark, part of the Northern Norway region.

Landslide events and warning performance

The performance of the service is evaluated by controlling the number, type, size and consequences of landslides, respect to the time/area and level of the warning and according to the definition of the awareness levels. The analysis is done based on a dataset of landslide events verified by the forecasters in the aftermaths of a weather event. The verified dataset is composed by 1052 landslides in the period from 2013 to 2019 (Fig. 4).

Respect to the previous analysis presented in Krøgli et al. 2018, the results presented herein are updated with the last 2 years of observations. The performance at regional scale is about 98%. Table 1 shows the warning performance in the analyzed period. The column "correct warning" includes both true negatives (days with green level and no landslides) and true positives (days with yellow, orange or red level, and with a certain number of landslides expected for that level). The numbers of landslides expected for each level are presented in Piciullo et al. (2017). The true positives are more difficult to verify, because of the difficulty to verify the real number of landslides. In this analysis we consider only the landslide events verified by the forecasters in the aftermaths of a weather event to define the true positives. We observe also that the number of false alarms is clearly reduced from 2013 to 2015 (Table 1) due to an adjustment of the threshold in Southern and South-Eastern Norway (Krøgli et al. 2018).

User's response to the warnings

An important user of our warning is the NVE staff working in the five regional offices (Northern, Central, Western, Southern and Eastern). NVE is not a primary emergency agency, but NVE regional staff is often called upon by municipalities (and the police) for advice during emergencies and crises and in the aftermaths of landslides and floods affecting settlements. If a landslide warning level is given (yellow, orange or red), NVE declares a kind of internal emergency response divided in two levels: "Emergency" and "High emergency". "Emergency" is declared on e.g. a major single landslide involving people and/or in case of landslide orange or red warning. "High emergency" is declared if round-the-clock effort is needed from NVE regional staff, due to e.g. large geographical extent of the hazardous event (many landslides widespread in the region) or because a

Table 1 Warning performance in percentage (%) for the period 2013–2019. "Correct Warning" (C), "False Alarm" (FA), "Missing Event" (ME), "Wrong level (between yellow and orange)" (WL)

Year	C	FA	ME	WL
2019	97.7	1.0	0.8	0.3
2018	98.1	0.5	0.5	0.5
2017	96.3	1.9	1.1	0.4
2016	98.4	0.8	1.1	0.3
2015	97.9	1.4	0.3	0.4
2014	92.9	5.2	1.2	0.7
2013	94.2	3.3	2.2	0.3

large number of people is affected. These two emergency levels always involve the head chief of the regional office, responsible for the region in which the forecast has been sent. A few key persons or more may be put in emergency or standby based on the extent and the level of the warning. In cases of a lower level forecast (yellow), a NVE regional office may be set in a mode of "increased vigilance", meaning that NVE is following the situation closely, but it is not implementing any further action at the moment.

Experiences acquired at NVEs Eastern regional office indicated that the perception of landslide hazards has increased in the region among responders, authorities and the population through the years and that the forecast service has become an important tool in the emergency response phase. Moreover, the NVE regional staff consider that the value of the landslide warning is strengthened in those areas where landslide hazard has been mapped. Municipalities are then given a possibility to initiate actions for specific areas/buildings depending on the type(s) of landslide forecasted. The available hazard maps can be visualized at (https://temakart.nve.no/link/?link=Skredfaresone).

The free subscription service by e-mail and/or SMS to the warning portal varsom.no is also particularly useful for the regional offices as it provides valuable information to the expertise and engineers working in NVE throughout Norway.

A user survey conducted in autumn 2019 shows that the awareness towards landslide hazards has increase in the last 10 years among emergency authorities. 428 people answered the survey: 2/3 of them are working at responder institutions like road authorities or municipalities and 1/3 were population. 59% of the local emergency authorities answered that they know about damaging landslides and the required actions, while in 2016 only 42% of them answered to the same question and back in 2009 only the 37%. This is not related to an increased number of landslides nationwide, but to a better hazard knowledge. The increased knowledge can be attributed to the establishment of the national forecasting and warning service and all others NVE systematic efforts to better prevent landslides, like the landslide hazard mapping program conducted nationally since 2011. In the 2019 survey, more than 80% of the emergency authorities said that they have made a local assessment after receiving a warning. About 70% said that they performed actions. Over 86% of the interviewed emergency authorities expressed that the warning service is very useful, and they consider it highly reliable.

Evaluation of the Norwegian LEWS

The organization, operation and maintenance of a LEWS is complex (Table 2). Periodic evaluation of LEWS can therefore be a difficult task, especially if all components should be evaluated at the same time. In this analysis we evaluate only some of these steps, indicated by underlined text in Table 2.

Strengths and limitations of the service

Figure 5 shows the organizational history of the Norwegian LEWS. Despite a sporadic attempt of thresholds development in the late 1990s (Sandersen et al. 1996), it is only after 2005 that a common national interest grows towards the mitigation of damages caused by these types of landslides. The service was operational after a test period of two years, with research and development (models, thresholds), warning tests, and organization building (guidelines, recruitment and training of forecasters).

In Fig. 6 we have assembled the main strengths and the main reasons of success, together with the most important short- and long-term benefits.

Among the most important challenges are:

(1) A poor understanding and a limited knowledge of rainfall- and snowmelt-induced landslides and their conditioning and triggering mechanisms (i.e. weather and ground conditions). There are few studies and past investigations of these landslide types and the quality of the national landslide database is still too poor. Consequently, this has important negative effects in the

Table 2 Requirements for operational LEWS. Main key components and steps (K.C.—Key component, S.—Step and R.—Requirement). Underlined text is further evaluated here

Requirements for LEWS
K.C. Risk knowledge and setting of the system (national and institutional involvement) *S: Identify landslide risks and needs to establish a LEWS. Identify national expertise, institutions, financial support and legal statements* **R. Landslides must be a risk (reliable and accurate hazard and risk analyses). LEWS is often the best and cheapest mitigation option for the society, (prefeasibility study, containing cost and benefits analyses). Political understanding and interest in the organization of EWS. Available financial support to start. Collaboration among scientific community and politicians. Scientific community with landslide expertise. Stability and long term politic**
K.C. Monitoring, forecasting and warning service (institutional, researcher and forecasters involvement) *S: Implementation of a warning model and a warning service* **R. Establishment of the service (internal organization). Legal mandate. Available landslide expertise. Training. Collaboration (multidisciplinary team). Guidelines and daily procedures** **R. Monitoring and modelling. Effective monitoring systems in appropriate locations. Supporting tools (software, hardware, web platform for sharing data) and daily maintenance. Functioning network for receiving data and forecasts. Reliable historical data. Reliable hydro-meteorological forecasting models and thresholds** **R. Daily operation and hazard assessment. Analysis and daily forecasts and model outputs. Functioning forecasts reception. Functioning supporting tools, models. Available forecasting expertise. Understanding the forecasts, model output, uncertainties. Objective interpretation of forecasts. Objective assignment of warning level. Weekly meeting and exchange experience. Freedom to do the daily hazard assessment without social pressure**
K.C. Dissemination and communication (institutional, researcher and forecasters involvement) *S: Implementation of a warning model and a warning service* **R. Warning service. Warning tools and platforms for communication available and functioning. Definition of warning criteria, warning areas and levels. Standards for warning text, symbols. Preparation of warning messages (text, map and level). Communication of uncertainties. Maintain contact with users and communicate risks, preparing learning material, videos. Use of social media**
K.C. Response capability (local users, forecasters, researcher, institutional, national involvement) *S. Evaluate the capability response of the system* **R. Emergency plan. Reception and understanding of the warning. Applying emergency plans, take actions** **R. Evaluation of performance. Analysis of what happened and performance analyses. Verification of damages. Verification of emergency plans application and if mitigation actions have been undertaken. Verification of landslide occurrence: control and registrations. Field campaigns after a specific event, close contact between forecaster and users. Evaluation criteria. Training and education, also of end-users to a correct interpretation of warning messages. Periodically evaluations of the entire system, propose changes to the organization or improvements to the system. Identify needs for improve scientific development, landslide hazard education at university level, review research strategy and balance between research and operation. Building up the credibility of the scientific institution**

daily landslide hazard assessment because (a) we lack of reliable thresholds for the entire country; (b) the thresholds are more reliable in those regions where past landslide records have been controlled or are more complete; (c) the lack of reliable historical records and thresholds may produce subjective assessments that depend on the forecaster's experience.

(2) The prediction of landslides triggered by local and short-intense rainfalls, product of convective clouds during summer, is a challenging task to perform with the available models and thresholds. The number of heavy rainfall events in summer is expected to increase in the future due to climate change (Hanssen-Bauer et al. 2017); the estimation of the expected rainfall amount and location is very uncertain and prediction models need to be tested; local short-intense rainfall (1–3 h) is seldom recorded by official rain gauges and the observed grid-data of rain on summer at 1 km^2, used as input in our hydrological model, is therefore often mislead. The NVEs hydrological models are running at 24 h basis. The impact of short-intense rainfall is often weakly related to pre-existing hydrological conditions (i.e. groundwater, soil water and river discharge). Due to the lack of reliable data (time of events, rainfall records, hydrological modelling), we have not yet calculated landslide thresholds for short-intense rainfall events.

(3) The prediction of landslides caused by rapid snowmelt in winter is also challenging because changes in temperature are not taken into account in our hydrological models.

(4) An important task for forecasters after sending a warning, is to verify the occurrence and extension of landslides. Therefore, an overview of spatial and temporal distribution, as well as number, type, and dimension of all occurred landslides events is strongly required. An event inventory (that ideally should register all landslides occurred during a specific weather event, Guzzetti el al. 2012) is necessary after a warning is sent, to evaluate if the warning level and the warning area were correct and, on the long term, to be used in the improvement of the landslide thresholds. NVE runs

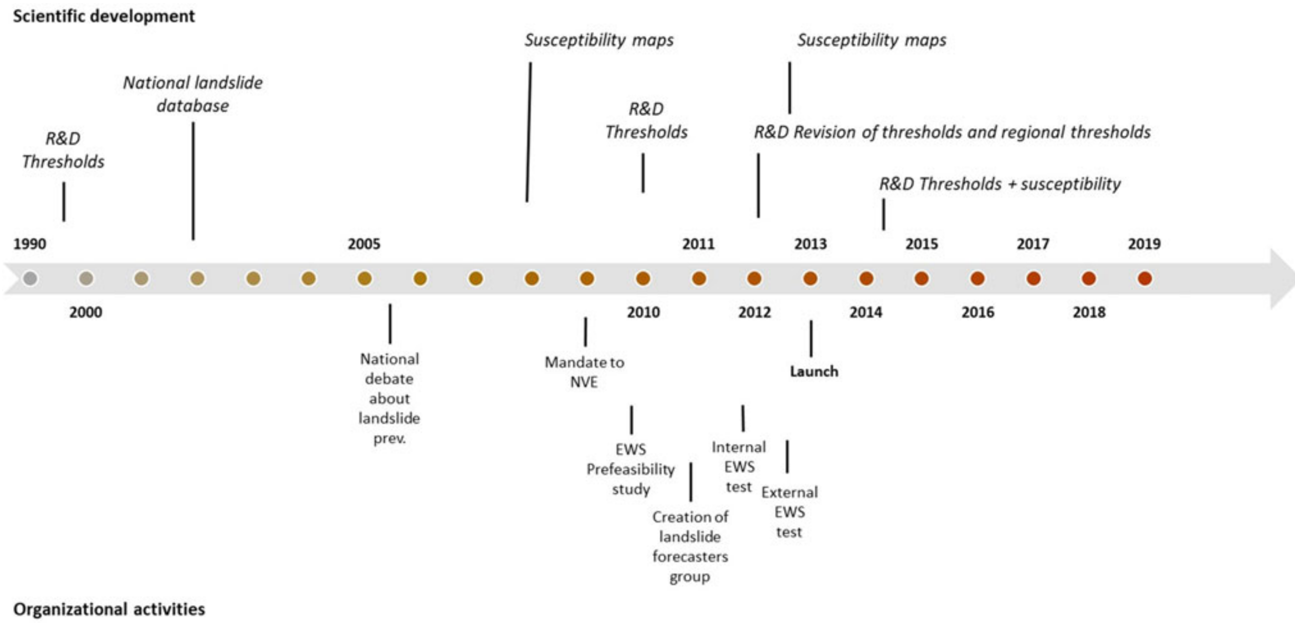

Fig. 5 Timeline of the organizational history of the Norwegian LEW. R&D stands for Research and Development

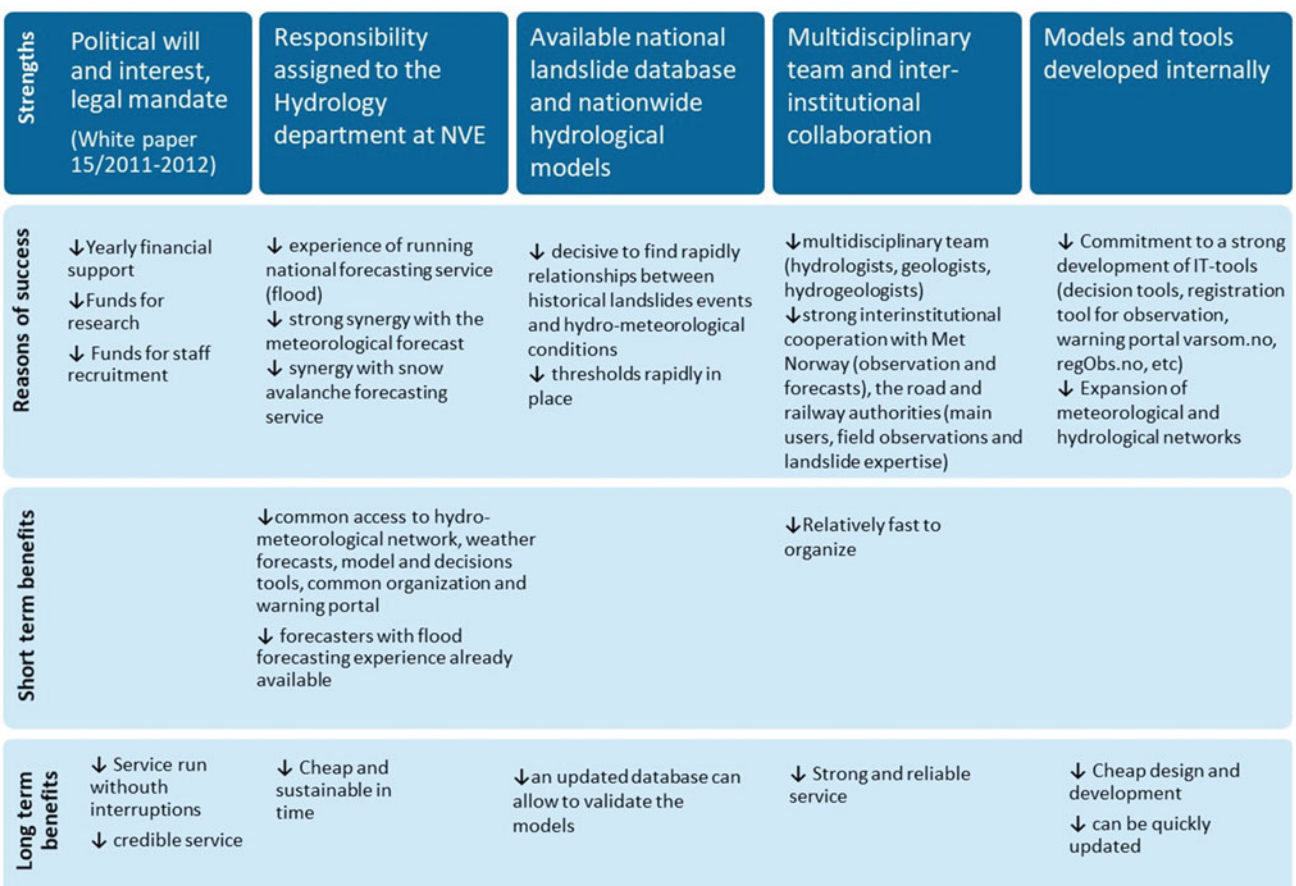

Fig. 6 Main strengths of the Norwegian LEWS

a national mass movement database in cooperation with others national institutes, where everybody can register landslide events (www.skredregistrering.no). Beside this database, NVE has developed other crowdsourcing tools to gather real-time observations from field (Krøgli et al 2018 and references therein). During a weather event many users, with variate landslide expertise, can register landslide events. Forecasters at NVE track the occurrence of landslide events under a specific weather event through media (radio, newspapers, TV) and register them in any of these tools. Beside these efforts there is not a systematic and not coordinated follow-up after landslide events, neither the preparation of event inventories after an event. Consequently, the landslide events are not systematically registered, and not systematically controlled and verified. Forecasters use a "verified landslide dataset" for warning performance analysis, but this verified information does not always match with the information in the database.

Conclusions

The landslide forecasting and warning service is in its eight year. The system is robust in terms of organization, human resources, financial supports, decision tools and forecasting models.

The service works well, predicting the main hydrometeorological conditions that can trigger landslides. The experience so far, indicates that several yellow levels were issued, when an orange level should have been sent instead. Only one day (the 22th of May 2013 in South-Eastern Norway) had red level during the period 2013–2019. It is too early to evaluate red levels after only 7 years of operation, because in general red level should occur very rarely (50 years return period in analogy to the national flood warning system). The tendency for improved performance may be explained both by more experienced forecasters, by better meteorological forecasts provided by MET Norway and by a better understanding of the uncertainty in the hydro-meteorological forecasts.

NVE is continuously working to rationalize and consolidate the service, running research projects to improve the precision and accuracy of the warnings. NVE is also improving the communication and build up users understanding. The success of such systems is like a feedback-loop. First the EWS need to be reliable enough to be taken into operation. Thereafter the users must be trained to use the available information. To ensure a proper response to a challenging situation, it is an advantage if the latter is a mutual process where the users needs are taken into account in the further development of the EWS. Sufficient coverage of landslide hazard maps is thus a key to extract the full advantage of the forecast service. NVE is continuously producing such maps for selected areas and municipalities in Norway.

We suggest to wait some years before evaluating the performance of the system. After 8 years it will be possible to see the results of the LEWS, but only if there is continuity of the service and annual events. We reccomend to start with a reliable landslide dataset and models of sufficient resolution (6, 3 h). Subsequently developing reliable regional thresholds and thresholds for short intense rainfalls. Heavy rainshowers in summer are a quite new phenomenon in Norway. There are still very few long series of rain records at hourly basis. To handle the challenges with short-intense rainfall and rapid changes in temperature NVE is currently developing a hydrological model running at 3 h steps. Future developments include landslides thresholds for 3, 6 and 12 h.

The service scores a high performance, but some steps are still challenging. The most time consuming and subjective task is the quality control of recorded landslides to be used for performance evaluation and threshold adjustment. The daily monitoring and systematic registration of landslide events has contributed to a better understanding of their physical characteristics and their spatial and temporal triggering conditions. In recent years, new technologies as use of drones and satellite images offer a possibility to register data more efficiently. Experience with these technologies for landslides in Norway, is however limited for the time being.

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