Railway geohazard risk management: some practical experiences with geohazard warning thresholds

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ABSTRACT
Geohazard risk affects the Quebec North Shore and Labrador Railway connecting an Iron Ore mine in Labrador City, NL to port facilities in Sept-Îles, QC. This risk derives from a range of geomorphic processes along the railway, including rockfall, earth landslides, washout (internal or overland erosion of the embankment) and river bank erosion. Risk is managed in accordance with widely accepted principles, including provision to monitor for conditions that may influence the current likelihood of geohazard occurrence. Bank erosion potential is monitored via stream gauge observations. Earth landslide and washout potential are monitored via rainfall observations in comparison with intensity-duration-frequency threshold curves. Rockfall potential is monitored via rainfall observations and time since last thaw. Each warning threshold has been re-examined over time to consider geohazard event and non-event observations. This paper discusses recent modifications to geohazard warning systems striking a balance between accuracy and practicality.

RÉSUMÉ
Le risque de géorisque affecte la voie ferrée de la Côte-Nord et du Labrador du Québec reliant une mine de minerai de fer à Labrador City (T.-N.-L.) à des installations portuaires à Sept-Îles (QC). Ce risque provient d'une série de processus le long de la voie ferrée, notamment les chutes de pierres, les glissements de terrain, le lessivage (érosion interne ou terrestre du remblai) et l'érosion des berges des rivières. Les risques sont gérés conformément aux principes généralement acceptés, y compris la disposition prévoyant la surveillance des conditions susceptibles d'influencer la probabilité actuelle de survenue de catastrophes naturelles. Le potentiel d'érosion des berges est surveillé au moyen d'observations de jauge de cours d'eau. Les glissements de terrain et le potentiel de lessivage sont surveillés via des observations de précipitations en comparaison avec les courbes de seuil intensité-durée-fréquence. Le potentiel de chute de pierres est surveillé via les observations de précipitations et le temps écoulé depuis le dernier dégel. Chaque seuil d'alerte a été réexaminé au fil du temps afin de prendre en compte les évènements géologiques. Ce document traite de certains des principaux changements au fil du temps, en montrant la nécessité de développer, de surveiller et d'affiner au fil du temps, des systèmes d'alerte qui établissent un équilibre entre exactitude et utilité.

1 INTRODUCTION

This paper presents the development, review and revision of geohazard warning systems for various geohazards affecting Quebec North Shore and Labrador Railway (QNS&LR), operated by Iron Ore Company of Canada (IOC).

The warning systems, or trigger action response protocols (TARPs), were developed for use by IOC to reduce risk along the QNS&LR for bank erosion, rockfall, washout and earth and debris landslide geohazards; there is also a separate TARP for potential earthquake-generated permanent ground deformation from landslides or liquefaction. These TARPs, used within the overall risk management context of the IOC Geohazard Management System (IOC-GMS), each have action thresholds ranging from Level 1 to Level 4, with each level corresponding to prescribed actions to reduce geohazard risk based on observed rainfall, stream flow, temperature or recorded ground motion from an earthquake. This paper focusses on adjustments made to the washout and landslide TARPs over the past three years.

1.1 Background

The IOC-GMS geohazard TARPs have been in place since July 2016 and have been reviewed and revised episodically with consideration for observed geohazard events and elevated thresholds which have not triggered geohazard activity. The landslide TARP (BGC, 2016a) and washout TARP (BGC, 2016b) were originally developed as separate systems, each based on rainfall intensity and duration. They were combined in 2017 (BGC, 2017a) to simplify the monitoring system. The rockfall TARP (BGC, 2016d) was originally developed in 2016, and updated in 2017 (BGC, 2017b). The bank erosion TARP (BGC, 2016c) was developed in 2016 and reviewed in 2018 (BGC, 2018a. The earthquake TARP (BGC, 2018b) was developed in 2018.

The TARP systems have evolved with experience of geohazard event occurrence and with observations of operational efficiency. In 2018, IOC noted that false alarms (i.e., elevated TARP levels with no accompanying geohazard event occurrence) were occurring relatively frequently, particularly in the northern end of the railway for washout and landslide geohazards, with the effect of slowing rail traffic and thus impacting operational efficiency of the railway, port and mine. The performance of the

TARPs was evaluated to determine whether modifications could be made, to improve operational efficiency without degrading risk management. This paper discusses a recent review; various options for further TARP modification are discussed, focusing on washout and landslide geohazards in the northern part of the railway.

1.2 Organization of the Paper

This paper contains the following main sections:

- High level overview of initial TARP development and early updates and revisions to the TARPs
- Analysis of factors affecting TARP warnings for landslides and washout geohazards in northern end of the railway
- Discussion of potential further enhancements of TARPs to optimize the balance between risk reduction and operational impacts

2 LANDSLIDE AND WASHOUT TARP DEVELOPMENT AND REVISION

TARPs used within the IOC-GMS are used to monitor changes in geohazard triggering conditions; each has four warning levels, ranging from Level 1 to Level 4. Geohazard event likelihood, and correspondingly the risk from geohazards, is expected to increase with increasing warning level, and the operational response varies accordingly. At Level 1, normal railway operations are permitted, and at elevated warning levels, progressively more conservative actions are taken, potentially including reduced track speed, patrols, inspections or traffic prohibition.

The TARPs for earth and debris landslides and washouts were originally developed with limited basis from pertinent literature or from formal records of geohazard occurrence along the railway. A major geohazard-inducing rain event in December 2010 produced numerous landslides and washouts, and this served as a qualitative baseline. A regional study of rainfall-triggered shallow landslides on steep slopes (Dagenais Du Fort, 2014) found that shallow landslides were likely when 24-hour rainfall exceeds 70 mm. This data point was used with longer-duration rainfall from the December 2010 event to delineate the threshold between Level 3 (sporadic shallow landslides possible) and Level 4 (abundant shallow landslides likely).

The washout TARP was similarly developed, in part, by examining antecedent rainfall conditions prior to several recent (i.e., previous 7 years) events. Consideration was also given to the estimated culvert capacities along the railway compared with expected runoff. Landslide TARP thresholds were defined as being parallel to rainfall intensity-duration-frequency (IDF) curves; the washout thresholds were slightly offset from rainfall IDF curves. Figure 1 shows the original landslide and washout TARP thresholds on the same plot, for comparison.

Early use of the landslide and washout TARPs in 2016 to 2017 suggested that they were functioning approximately as intended, with relatively few days observed with elevated warning levels, and most of the year (> 80 to 90%, varying with location along the railway) at Level 1. However, in an effort to simplify the system, recognizing that the two TARPs had similar thresholds, they were combined into a single TARP for both shallow landslides and washouts, with the combined thresholds coincident with the original landslide thresholds. This had the result of yielding somewhat more conservative thresholds for washout geohazards. The potential cost / effort associated with this additional conservativism is offset by system simplicity and uniformity of response and reduces the likelihood of an error when changing operating protocols along the railway.

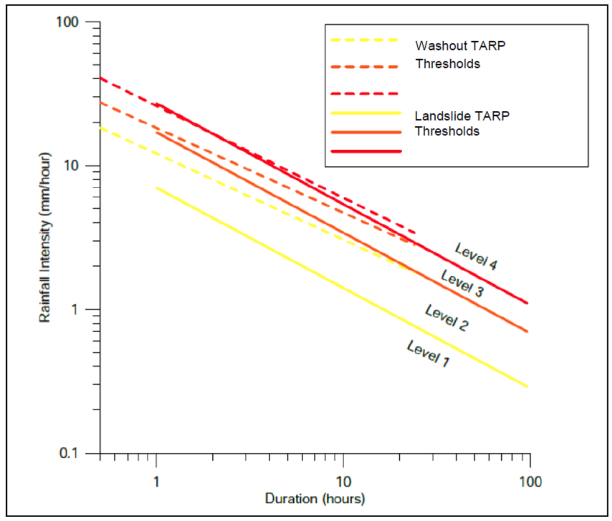

Figure 1. Original (2016) shallow landslide and washout TARP thresholds.

3 ANALYSIS OF NORTHERN TARPS FOR WASHOUT AND LANDSLIDE GEOHAZARDS

Operational experience in 2017 and 2018 yielded relatively frequent elevated warning levels with no accompanying geohazard events (i.e., false alarms). In the northern part of the railway closer to Wabush, NL, where weather stations (and TARP response areas) are widely spaced, this resulted in frequent slow orders or traffic stoppages affecting significant lengths of rail; as such, the cost of response was perceived to possibly outweigh its risk reduction benefits. BGC was asked to study the TARP levels in greater detail, to determine whether different thresholds or response would be appropriate in the north, in an effort to improve the balance between risk reduction costs and benefits.

QNS&LR is approximately 400 km long and traverses a range of terrain and climactic conditions which affect the spatial distribution of geohazards and temporal frequency of geohazard-initiating conditions. IOC has installed eight weather stations along the railway. Their locations and associated monitoring extents are shown in Figure 2a.

From south to north, the railway rises gradually from the rail yard at the port facilities in Sept-Îles (see Figure 2a) to approximately 100 m elevation near mile 55 of the Wacouna subdivision, thereafter rising steadily to approximately 600 m elevation near mile 90 and beyond to the mine at Labrador City. The railroad therefore traverses a lowland up to about mile 55, a transitional zone between the lowland and upland from mile 55 to mile 90, and an upland beyond about mile 90. The drainage divide separating land draining to the Saint Lawrence from that draining north, which coincides with the provincial border between Québec and Newfoundland and Labrador, is at about mile 147, beyond which the land slopes gently down to a plateau in the north.

Geological conditions are broadly reflected in the physiographic transitions described above, as shown in Figure 2b-c. The lowlands tend to contain glaciomarine soils, including weak clays, as well as a veneer (i.e., thin cover) of clayey glacial till. The uplands are generally covered by a blanket (i.e., thicker cover) of sandy glacial till. The underlying bedrock is generally crystalline hard rock of the Grenville Province of the Canadian Shield, transitioning from migmatite and granite in the southern lowland to tonalite gneiss and high-grade gneiss in the northern upland. The soils in the southern lowland, particularly glaciomarine soils, are more prone to earth and debris landslides than the sandy till that is widely present in the north.

Drainage characteristics may be expected to vary according to physiographic differences. Figure 3b shows the relative proportion of storage (i.e., lakes and ponds) in drainage basins with outlets crossing the railway, and Figure 3c shows a measure of relief within the storage basins. The presence of storage within a drainage basin tends to delay the transmission of water from the headwaters to the outlet, resulting in a muted hydrograph with generally lower, later peak flows than an equivalent basin without storage for a given runoff event. The presence of relief in a basin suggests generally higher slopes, resulting in shorter, steeper flow paths from the headwaters to the outlet, resulting in earlier, higher peaks than an equivalent basin with less relief. An examination of Figure 3c suggests that relief is generally higher in the south, and lower in the north, and basin storage is typically low in the south, increasing significantly in the north. These two factors, taken together, suggest that, all else being equal, similar rainfall or snowmelt will produce higher peak flows more quickly for southern drainage basins than those in the north. This agrees with IOC observations (D. Sirois, personal communications, 2018) that storms in the north tend to produce lower observed runoff in creeks and culverts than similar storms in the south.

The drainage basin characteristics discussed above suggest generally lower potential for washout geohazard occurrence in the north, since these depend on runoff magnitude in relation to flow-carrying capacity, typically at culverts. However, an examination of culvert capacity in comparison with expected runoff (Figure 3d) from the culvert database in the IOC-GMS suggests that a larger number of culverts in the north are undersized relative to expected peak runoff. Culvert capacities depend largely on their cross-sectional area, and the peak runoff used in IOC-GMS was estimated according to the Rational method using uniform, simplified assumptions. Notably, runoff coefficients were assumed constant along the railway, and catchment topography and basin storage were ignored in the calculations. The presence of more frequent undersized culverts in the north, as shown in Figure 3d, may suggest that the original railway designers took account of basin storage in the sizing of culverts, selecting typically smaller culverts in the north than the south for the same basin size. As such, the average culvert size acts in opposition to the basin runoff characteristics discussed previously, which provided evidence for lower, more subdued hydrographs in the north. Where the culverts are undersized this effect is reduced or eliminated.

Figure 3e illustrates the distribution of storm duration by weather station, and Figure 3f shows the average hourly precipitation (over the period of observation) at each weather station. Here we define storm duration as the period of time over which continuous rainfall of any intensity is observed from one hour to the next; the average hourly precipitation serves as a proxy for total annual precipitation. In these plots, longer duration storms and higher average rainfall each suggest a higher likelihood of washout geohazards and may be suggestive of a higher potential for landslide geohazards, both of which are sensitive to extreme rainfall events. The southernmost station – Gagnon Sud – has distinctly different characteristics than all other stations, with higher average precipitation, both as rain and as snow, and longer storm events. Mai Terminal stands out as being unusual, with lower overall precipitation and shorter storm duration than all other stations. If this is a true representation (i.e., not reflective of data errors at the weather station), then it suggests a distinctly different (i.e., drier) character of precipitation near the middle of the railway than elsewhere. All other weather stations show relatively similar character for both storm duration and average precipitation, each within the bounds of uncertainty at the other stations. These results suggest that the potential for washout and earth and debris landslides is highest near the southern end of the railway and may be distinctly lower than elsewhere near Mai Terminal, being relatively uniform elsewhere along the railway, but markedly lower in the north than in the south.

Figure 2d shows numbers of washout and landslide sites, separately, in 5-mile bins, for sites of all risk levels; Figure 2e shows moderate or high-risk sites, and Figure 2f shows only high-risk sites. The spatial density of geohazard sites is much higher in the south than in the north, and High Risk (Level 4 and 5) geohazard sites are infrequent in the north, with Level 5 or higher sites being almost entirely absent north of Wacouna mile 100. Only two landslide geohazards and two washout geohazards of Level 5 or higher are present between mile 100 and the north end of the railway. Therefore, the risk associated with these geohazards is more concentrated in the south end of the railway.

The differing conditions along the railway from south to north, as discussed in the preceding paragraphs, lead to meaningful differences in geohazard risk for washouts and earth and debris landslides. The meaning of elevated TARP levels (i.e., Level 2, 3 or 4) is therefore different in the north and south, and it follows that different approaches can be taken to respond to elevated TARP levels with roughly equivalent degree of risk reduction.

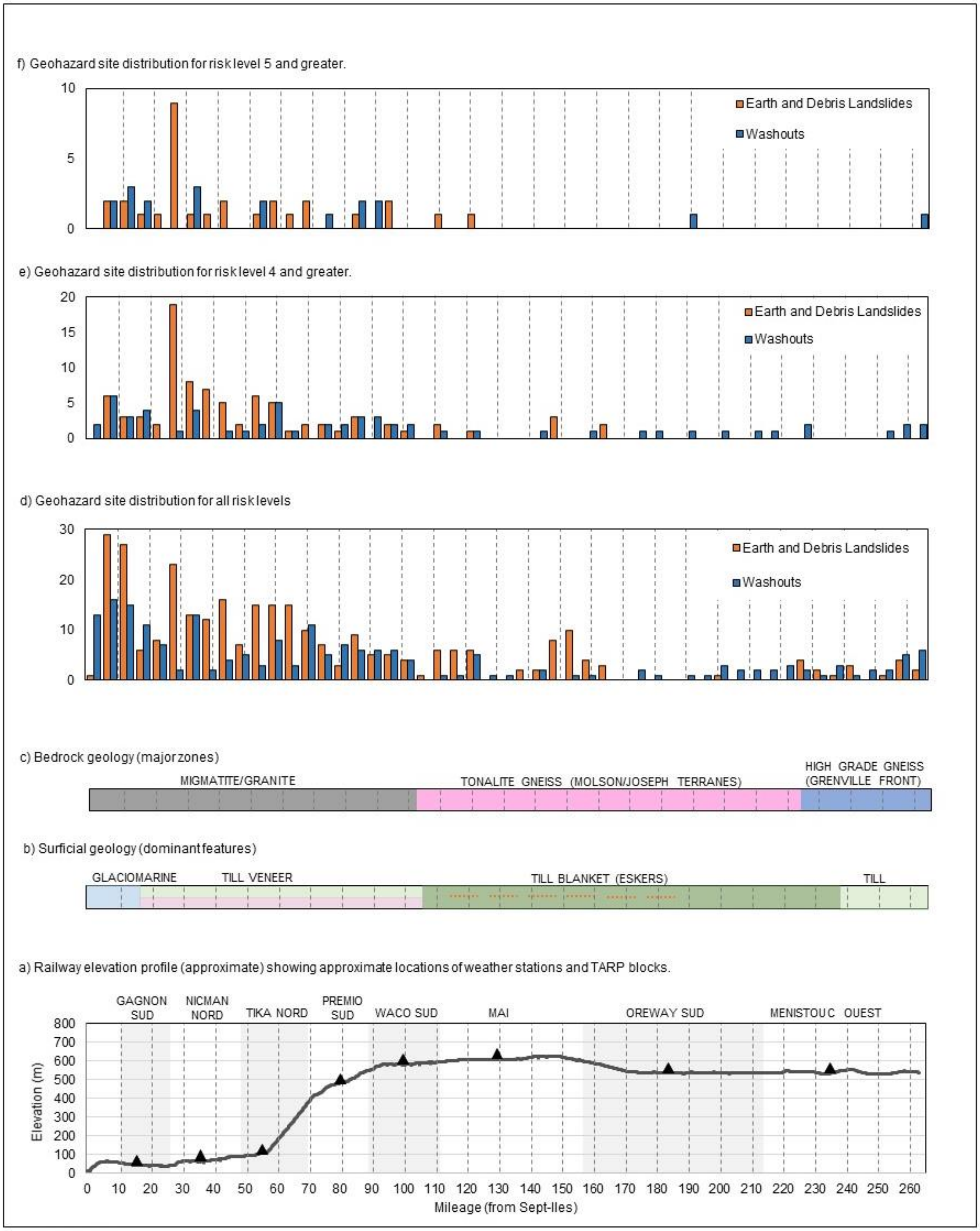

Figure 2. Railway elevation profile with weather station names and locations (a), geology (b-c), and geohazard site distribution (d-f).

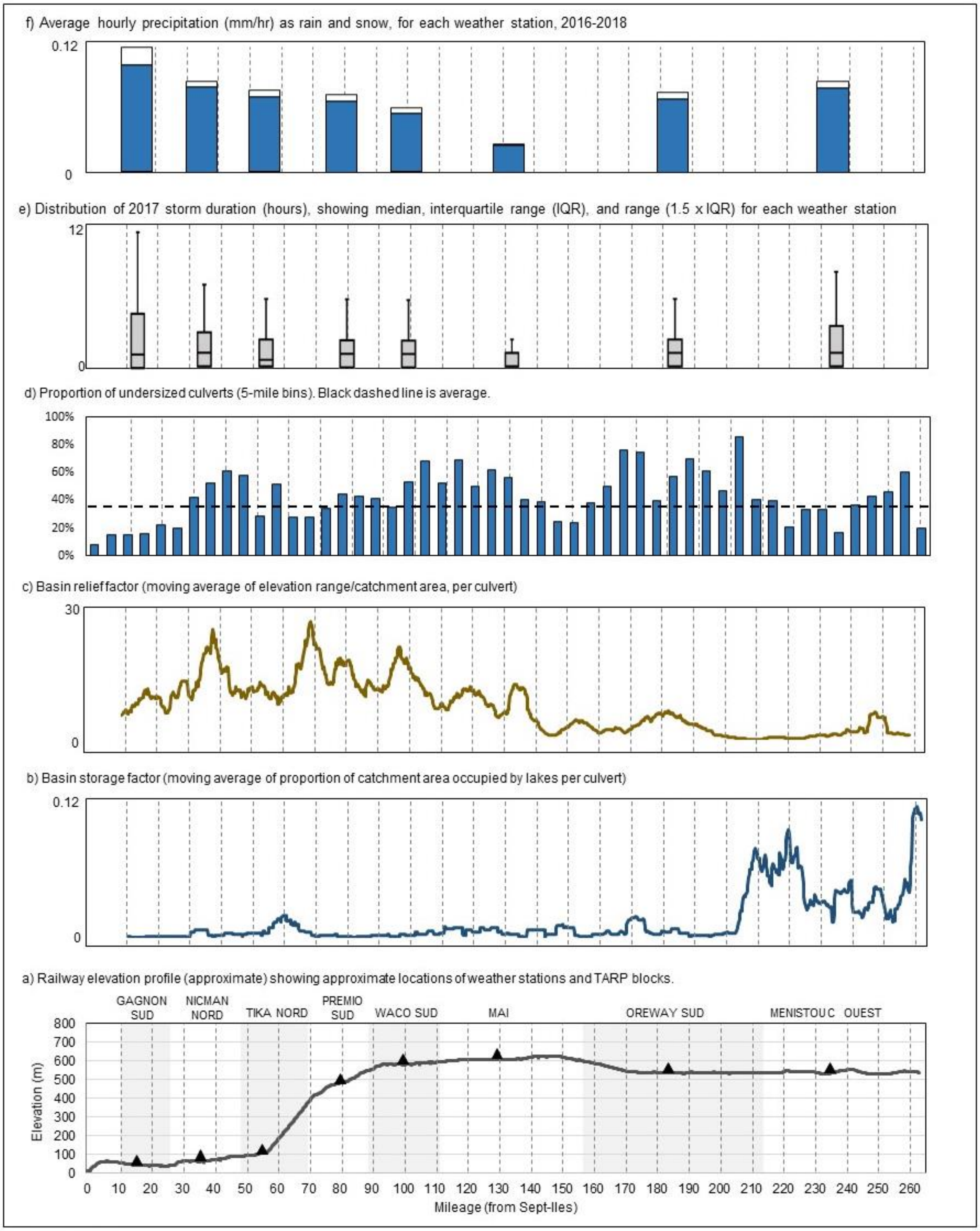

Figure 3. Railway elevation profile (a), geology (b-c), and geohazard site distribution (d-f).

5 DISCUSSION

TARP revision options were developed to better accommodate observed operational and physiological differences between southern and northern parts of the railway. The analysis presented above demonstrates a sound basis for a potential revision.

There are three general approaches available for adjusting the response to elevated warning thresholds:

- Option 1: Revise the thresholds based on geographic area (e.g., use higher thresholds in the north to reduce the number of warnings).
- Option 2: Retain the same thresholds along the whole railway but apply different response protocols based on geographic area (e.g., treat Level 3 and 4 in the north the same as Level 2 and 3 in the south).
- Option 3: Subdivide the railway into smaller areas (e.g., focus the TARP response only on areas with a high density of geohazards, or only at the specific locations of identified geohazards, such as High and Critical Risk geohazards, or Level 4 and higher).

Option 1 would be relatively simple to deploy, and would minimize operational confusion, since the differences would be embedded in IOC-GMS; however, there could be difficulty justifying the selection of revised thresholds. Option 2 has the advantage of being clearly defensible on the basis of the analysis presented in Section 3.0 but comes with the risk of operational confusion and associated inefficiency. Option 3 is a variation on Option 2, where the response is not varied in scope, but rather is focused in space. This approach may have the best overall operational efficiency, in that it could minimize the need for external resources (i.e., expert review from engineers or geologists during high warning levels) and focus the application of internal resources in space and time

In considering the preferred approach(es), we first examine the washout and landslide geohazards separately, since their occurrence depends on different factors, and they were originally managed by separate TARPs prior to consolidation in 2017. No change to current approaches appears warranted for either geohazard type up to at least the end of the area monitored from Tika Nord. The reduction in risk density for landslide geohazards permits a change of response approach for that geohazard type north of Tika Nord, and may permit a more significant change in approach, given the more rapid decrease in aggregate risk as compared with washout geohazards.

The recommended next steps are:

- Each of the precipitation thresholds for landslide and washout TARPs be increased for the northern stations, possibly in both intensity and duration. Selection of appropriate thresholds requires further examination.
- The group of northern stations to be considered for the revised thresholds includes Mai Terminal, Oreway Camp, and Menistouc west
- The railway continues to monitor landslide and washout geohazards in northern areas, as well as the impact of different rainfall intensity and duration on peak flows and shape of hydrographs at culverts. Better calibrated TARP thresholds may be possible in the future, based on these observations.

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