CHAPTER 1

Use of high resolution spatial and climate data to evaluate airport runway surface evenness flooding potential

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Keywords

Tarmac surface roughness evaluation, airport runway, airport taxiway, LiDAR, spatial parameters, climatology, runway surface conditions, international airport, climatological, precipitation, weather

Introduction

Airports offer a lifeline in terms of transportation of people and essential goods. They are vital for insular environments such as densely inhabited islands such as the Maltese archipelago. Continuous research is therefore necessary to continue improving operations by introducing to the airport industry new technologies and innovations stemming from other fields. This study offers a show case example on which Malta's airport industry can make use of innovative solutions to meet the demands posed by international regulations in the aviation sector.

Aircraft safety is a highly important aspect in the field of aviation transport management. There can be numerous hazards posed to the aircraft while in operation on the runway, especially during landing and takeoff. Plane safety during these two critical phases is especially related to both external (i.e. those related to the weather, especially to rainfall intensity) and internal (i.e. those related to the pavement macro texture and the friction properties runway conditions) conditions (Cao et al., 2014). However, these two can be intricately linked together as discussed further below. Impacts can be significant and varied, ranging from additional costs related to airport labour, equipment and materials, passenger delay, carrier delay and aircraft damage costs.

Weather conditions play a significant role aircraft safety. According to Benedetto (2002), accidents related to adverse weather amount to 29% of the total, especially during landing and takeoff. The intensity of significant weather impacts varies depending on the airport and its local climatology. Extreme heat, torrential rains of short durations, lightning etc are characteristic events in warm and relatively dry climates such as that of the Maltese islands. The evolution of transient rainstorms can create hydrological problem especially if long-enough climatological trends are not considered at the project phase of the design, construction and maintenance of the runway itself.

Heavy rainfall could impart severe and adverse consequences to aircraft. When an aircraft flies under rainy conditions, particularly during landing and takeoff phases, its flight safety can become under high risk. The scope of this chapter goes beyond such risks to aircraft; however, a short list of adverse risks include reduced visibility, reduced accuracy of aircraft measuring instruments, enhanced downward forcing and backward momentum to the upper wing surfaces and front part of the fuselage, condensation of water vapour above the air foil that could lead to destabilization of the boundary layer, increased roughness of the wing surfaces, and increased aircraft mass.

What is more relevant here is the increased danger caused by the resultant standing water on the runway especially during both aircraft landing and takeoff. Large accumulations of water due to runway unevenness can lead to 'hydroplaning', which tends to cancel out the braking action, resulting in longer stops or even sliding off the main runway. Empirical evidence shows that even small amounts of water on the runway may have a significant effect on aircraft performance (ICAO-RASG-APRAST, 2013). This emphasizes the need to have good drainage on runway surfaces since the drainage capabilities of any runway exposed to heavy rain can be exceeded, especially if surface maintenance has been overlooked. Runway unevenness may lead to the formation of water pools as shallow as 3mm in depth that can start to trigger hydroplaning. It is therefore necessary and important to prevent these from forming as much as possible. This is normally provided by adequate longitudinal and transverse sloping of the runway, as well as by a reduction of its surface roughness.

Hydroplaning is the cause of many aviation accidents (Aviation Accidents, 2018). A well quoted accident is that of 8/10/2004 in Bangladesh when an aircraft headed off a flooded runway due to the failure for braking while takeoff. The physical aspects of the water film affecting the braking performance include its thickness (which in this case is of primary concern), viscosity, temperature and density (Agrawal, 1986). An increased water thickness on a runway surface will in turn decrease available the friction coefficient which is a function of speed.

In addition, uneven runway surfaces directly influences aircraft components during takeoff and landing maneuvers, forcing higher material stress and fatigue which could lead to breakdown of mechanical parts (such as cabin vibration, extreme g-force, loss of adherence, etc).

The evaluation of runway roughness requires series of different measurements which are often subject to strict rules and international standards. Moreover, the kind of instrumentation and their required precision and accuracy are mandatory, not mentioning the modality of the data output and reporting. Surveys of the surface characteristics of airport runways are generally made to verify the flow of water from the surface and to guarantee a perfect surface regularity that guarantees safe aircraft maneuvering. Determining the runway surface roughness has become important in order to verify the adequate international standard requirements. According to ICAO, which is the International Civil Aviation Organisation that regulates civil aviation with the aim of standardizing procedures for air traffic management of airport runway and taxiway, supervision and maintenance of airport runway are based on the adoption of a Pavement Assessment Programme (PAP). International procedures in Malta are ratified by Transport Malta through its Civil Aviation Directorate. PAP supports methods surveying methods that examine the runway condition and without causing any damage or modification to the pavement surface (ICAO, 2001).

Traditional tachymetric surveys aim to verify at a high precision the main slope axes of the runway, taxiway and apron area, allowing the evaluation of their roughness parameters. Traditional topographic surveys make it possible to measure coordinates of the whole pavement through control points. However, the use of the total station has strong limitations due to the required point density in such cases, equal to the spatial continuity of the acquired information (usually measurements are taken at best with a grid of 10 m by 10 m). This drastically limits the possibility of holistically evaluating any localized deterioration over the entire runway.

The scope of this study is to show how the use of airborne LiDAR can in principle be used as an alternative runway control instead of traditional tachymetric surveys. Considering the performances of the most recent LiDAR instrumentation in terms of range, accuracy, point density and rapid acquisition, such instrumentation is bound to offer an interesting opportunity to measure the degree of runway unevenness and identify the current runway surface conditions to highlight problematic areas that could potentially give rise to wet surfaces or the occurrence of water patches or standing water. This exercise is relevant to ICAO Regulation requirements – 309.305(a)(6) stating that pavements shall be sufficiently drained and free of depressions to prevent ponding that can either obscure marking or impair safe aircraft operations. One important objective of our experimentation is to define, from an operative and computational process, a good index that can be used to quantify and spatially map runway surface unevenness from LiDAR.

This study is also tied to an assessment of the likely risk posed by extreme rainfall events on the basis of climatological study over Luqa airport, relative to other geographical locations in the central Mediterranean; including the determination of the return periods of extreme weather variables (such as rainfall rates and hailstorms) over Luqa airport which could pose potential flooding problems over the short and medium-term periods of time. In doing so, this study tries to provide some fundamental information in support of any future actions required to understand, monitor and predict runway flooding during severe weather conditions.

Methodology

This section describes ways how climatological rainfall characteristics and related hazards over the Maltese islands, particularly over Luqa airport, were gathered and analysed with a view of looking at the existence of risks to runway flooding, and therefore enable airport management and air traffic controllers to take the necessary protection measures.

It is important to point out that this study was carried out in 2018, after which intensive maintenance works were carried out at parts of the runway to increase its safety. These included runway re-surfacing as well as the installation of rainfall flood sensors at critical points along the runway.

In this study, the term ‘weather extreme’ applies to whenever the values of particular meteorological variables go beyond pre-defined (i.e. climatological) thresholds. A ‘return period’, or recurrence interval is hereby defined as an estimate of the likelihood of an extreme event to occur.

Local trends in rainfall: Climatological precipitation data over Malta Luqa Airport were collected from the European Climate Archives.

Two precipitation indices were chosen for this analysis: (1) CWD (Maximum number of consecutive wet days; the highest number of consecutive wet days where precipitation is more or equal to 1 mm a day), and (2) R20 (Heavy precipitation days with more than 20 mm, where days with precipitation of more or equal to 20 mm a day are counted). The entire dataset covered the period 1973-2013.

Analysis of extreme precipitation events: Additional meteorological data was gathered from land observations reported by the WMO climate station situated at the Luqa Airport (Malta), included rainfall levels and rates, occurrences of hail, etc. In this study, rainfall rate is the linear accumulation depth at ground level per unit time (usually in mm/h) used to characterize rainfall at ground level.

Time-series trends: Surface meteorological observations published every 30 minutes by Malta's Climate station at Luqa Airport were analysed. Only the long-term trends of the occurrence of hail events (1973-2009) and the maximum hourly rainfall (1959-2015) rates were analysed in view of time constraints available for this study.

This part of the statistical analyses incorporated data homogeneity testing, cumulative density functions, non-parametric correlation analysis and return periods, were carried out on the basis of the reference meteorological and hydrological data.

Topographical and surface texture information: Runway topographic data was derived from European Regional Development Funds (ERDF) project carried out in 2011 aimed at improving the national monitoring programmes on water, air, soil, noise and radiation. This data set consists of a 1m grid resolution covering the entire Maltese islands with a stated height accuracy of less than 10cm and with a generated LAS point cloud of 4 points per meter (ERDF 156 data, 2013). A set of high resolution 1m x 1m pixel raster maps were available by this project and used as the basis for analysis by this study. Dedicated hydrological raster processing was carried out on this dataset to generate a unique set of high-resolution GIS-raster maps describing hydrological characteristics such as the 'topographic wetness index' (TWI), which identifies pixel cells situated in depressed areas having a small vertical distance to a water channel.

The use of this index rests on the fact that topography is a first-order control on spatial variation of hydrological conditions. Since topography affects the distribution of moisture accumulation, this index has been developed to take into account the upslope contributing area and geometric functions. TWI was developed by Beven and Kirkby (1979) as part of the runoff TOP-MODEL and can be defined as shown below:

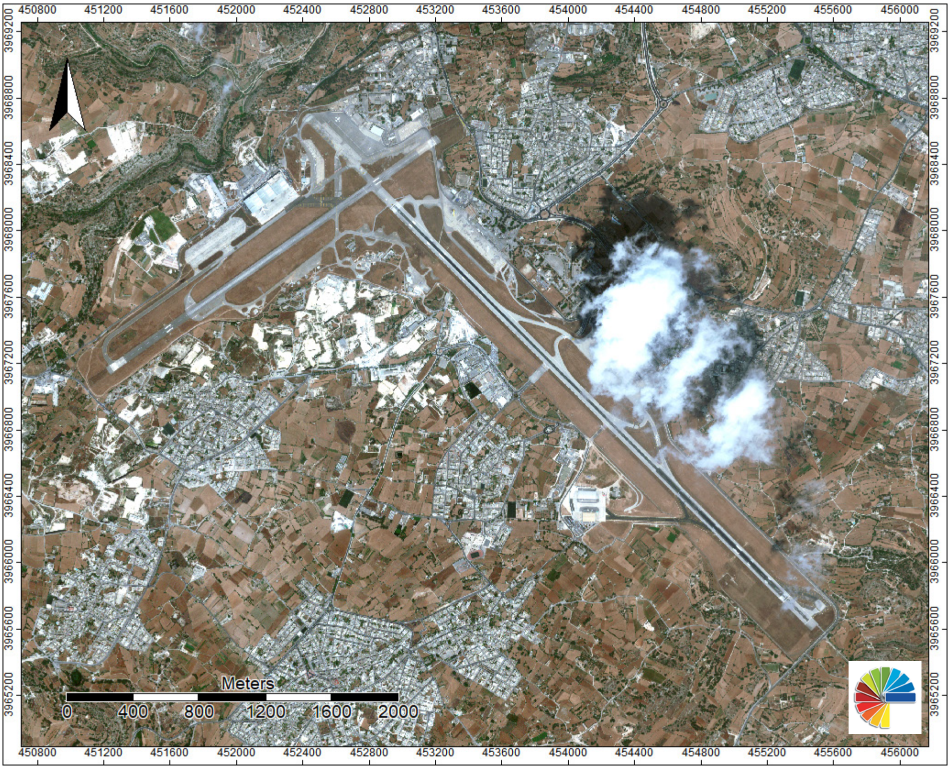
$$TWI = \ln(\alpha/\tan\beta)$$

where α is the local catchment area draining through a certain point per unit contour length and $\tan\beta$ is the local slope. The TWI has been used to study spatial scale effects on hydrological processes (Beven et al., 1988; Famiglietti and Wood, 1991; Sivapalan and

Wood, 1987; Siviapalan et al., 1990), to identify hydrological flow paths for geochemical modelling (Robson et al., 1992) and recently for lava flow paths (Cando-Jacome & Martinez-Grana, 2019). For this study, the TWI was calculated from the LiDAR dataset available.

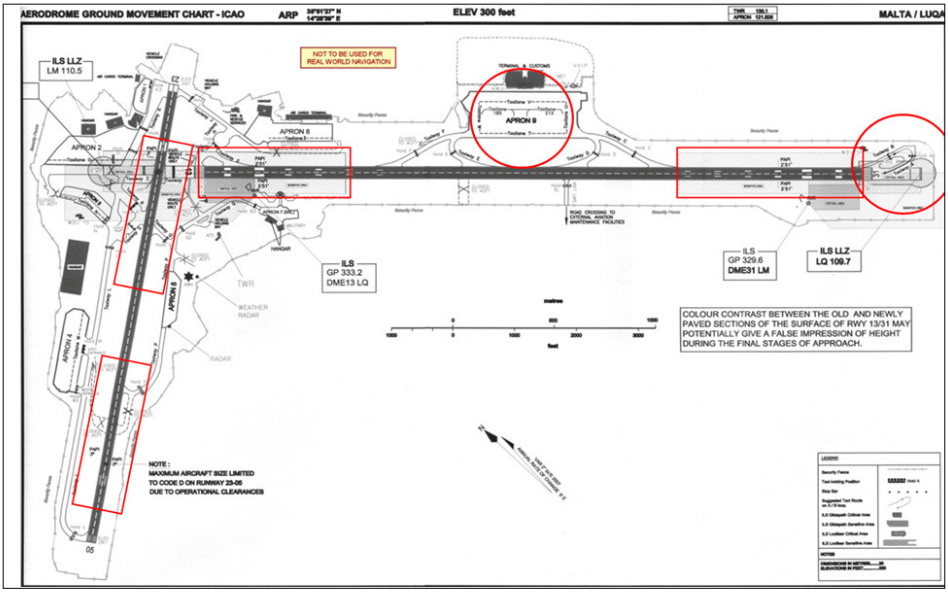
Figure 1 shows a map of the Malta LUQA runway (ICAO: LMML). Runway 13/31 measures 3544 x 60 meters while the shorter runway 05/23 measures 2377 x 45 meters.

Figure 1: Map of the Malta LUQA runways. Coordinates: N35'51.45' / E14'28.65'. Elevation is 297.0 feet MSL. Magnetic Variation is 3° East.



Of particular interest are three main points at Luqa runways, these being: the touchdown and takeoff points along runways 31-13 and 05-23, Apron 9, and TWY A and B at the extreme end of runway 31 (insets in red; fig. 2).

Figure 2: Areas of interest residing within Malta Luqa Airport (ICAO: LMML).

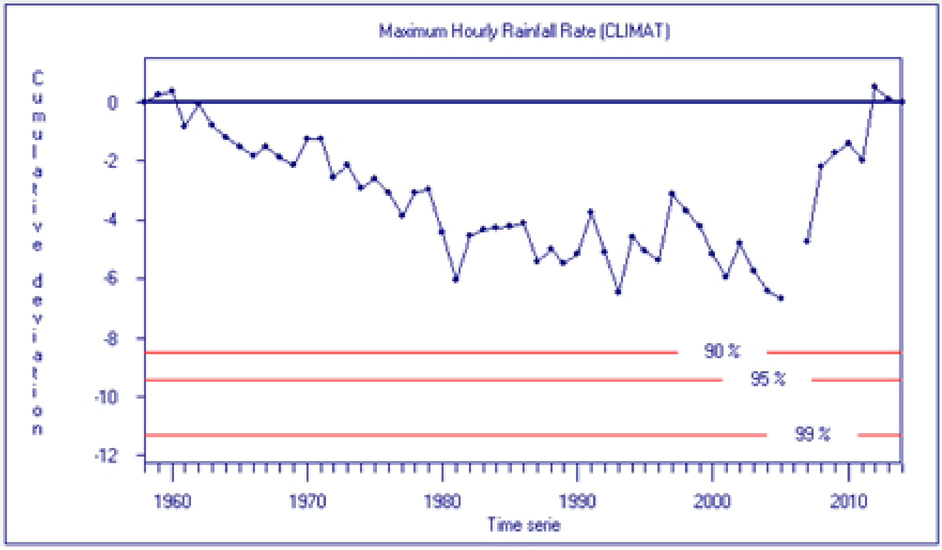


Results

Weather extremes and return periods.

The cumulative deviations from the mean of the maximum hourly rainfall observations for the period 1959-2015 (n=52) are shown in fig. 3. The vertical axis was rescaled and lines presenting various probabilities at which the homogeneity of the data can be rejected are shown. Since the values fluctuated far off from the lines where homogeneity is rejected, the data of the time series is considered to be homogenous (at 99% confidence level) with no breakpoints.

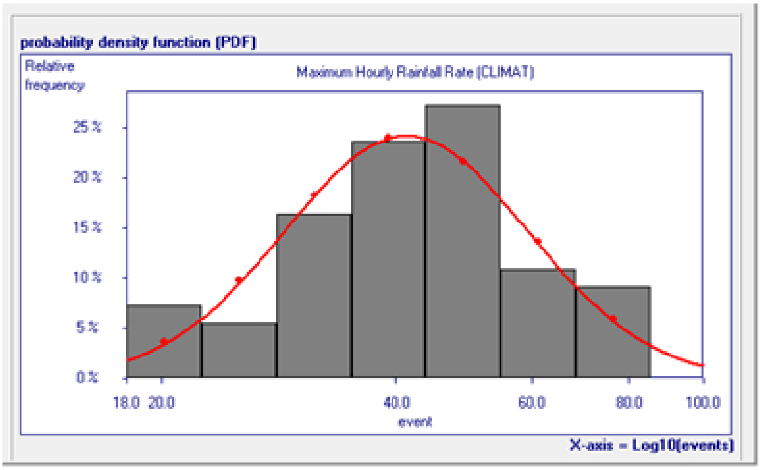
Figure 3: Homogeneity test for the time series of hourly maximum rainfall rate for Malta Luqa Airport (Malta LMML, WMO Climate Station) for the period 1959-2015. Data homogeneity is acceptable at 99% CL. Data for 2006 and 2007 are missing from dataset.



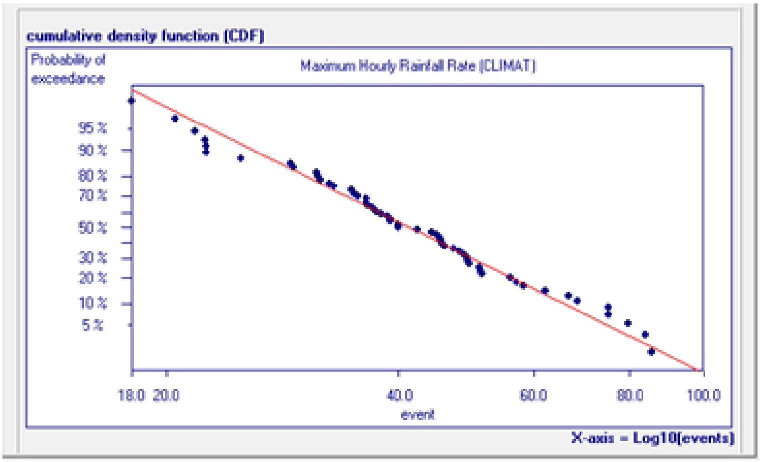
The probability plot (i.e. both the probability density function and cumulative density function) of the maximum hourly rainfall rates versus their probabilities of exceedance is shown below (fig 4a-b). The scale of the event was transformed to log10 for best and most significant distribution at 95% level with an R2 of 0.98.

For example, the extreme rainfall event that occurred in 2012 at Malta Luqa airport showed an hourly rainfall rate of 84 mm hr-1. By plotting the value on the probability plot (fig. 4b), it is evident that the event was one of the highest throughout Malta's record period for this parameter. The return periods of hourly rainfall rate are shown in table 1. Statistically, the return period to reach or exceed the 2012 maximum hourly rainfall rate record is estimated to be around 41 years under current climatic conditions. However, other return periods which can be deemed as significant for the safety of aircraft landing or taking off from Luqa airport are also valid and having shorter return periods. This means that risk of runway flooding is present.

Figure 4a-b: Probability and cumulative functions (PDF and CDF; both significant at 95% level) of the maximum hourly rainfall rate for Luqa Airport (Malta, WMO Climate Station) on log10 probability for the period 1959-2014, with the highest hourly rainfall rate of 84 mm hr-1 recorded during the September 2012 event. Distribution of both PDF and CDF are acceptable at 95% CL



(a) Probability density function of maximum hourly rainfall rate.



(b) Cumulative density function of recorded maximum hourly rainfall.

Table 1 shows the estimated hourly rainfall rate for Luqa Airport (Malta LMML, Climate Station) for selected probabilities and return periods from the probability plot (fig 4a-b).

Table 1: Estimated hourly maximum rainfall rate for Luqa Airport (Malta LMML, Climate Station) for selected probabilities and return periods as derived from the probability plot shown in fig. 4a-b.

Probability of exceedance (%)	**Hourly rainfall rate (mm hr-1)**	**Return period (years)**
1	95.8	100
2	86.8	50
5	74.9	20
10	65.6	10
20	56.0	5
50	41.3	2

The total number of occurrences with solid precipitation (i.e. hail) during the period 1973-2009 is seen to be generally on the decline. The annual records varied between 400 (1974) and 5 events (2004). The average number of hail events for this 37-year period is 155.4 per year. The negative trend (which is significant at 95% confidence level) however, potentially reflects Malta's changing climate, tied to a decreased frequency of solid precipitation over Luqa airport. A shift is also detected in the number of yearly hail occurrence throughout the study period. The homogeneity test shows a clear change of slope in the year 1990. Over the period 1973-1990 the total number of yearly hail events was above normal while over 1991 – 2009, the opposite pattern can be observed. It is important to note that the estimation method remains the same for both periods. This is the best available local data that is available for the occurrence of this meteorological phenomenon specifically derived from Malta Luqa Airport.

The reference period 1973-2009 can be therefore split up into two statistically significant periods which have different means: 1973-1990 with a mean of 265 hail events and 1991-2009 with a mean of 51 events. The jump in the mean between the years 1990/1991 separates the two periods. Based on best probability plot (R2- =0.93), the return periods of occurrences of hail (and therefore a higher probability to record extremes) are shown in table 2.

Table 2: Estimated return period of number of hail events for Luqa Airport (Malta, Climate Station) for selected probabilities and return periods derived from the probability of exceedance plot.

Probability of exceedance (%)	**Yearly occurrence of hail**	**Return period (years)**
1	451	100
2	417	50
5	365	20
10	318	10
20	262	5

The estimated return periods of between 50 and more years must be considered with caution. According to the official definition given by IPCC (2007), climate change is a change observed over a time period of 30 to 50 years or longer, and the time series used to derive the return periods might not contain a strong enough climate signal of such change (what Goodwin & Wright [2010] identified as a 'sparse' reference class for a typically 'chaotic' weather process). Moreover, being based on past values and records, statistically-derived return periods are mathematically possible on the assumption that the variability between past and future data sets remains stationary and that future time series will reveal frequency distributions similar to the observed ones. As the number of observations gradually increases, the error in determining expected return periods diminishes. Overall however, a period of 30 years and over (such as this study) is considered to be very satisfactory for this study.

Locating flood-prone areas on the runway surface.

Following detailed morphometric analyses of LiDAR data, the likely presence of runway tarmac surface depressions that can hold standing water and leading to damp, wet and water patches along extended parts of the runway were identified. These terms in italics are further defined in Annex 6 and 14 of ICAO circular 329. Standing water refers to accumulated water on the runway surface caused by heavy rainfall or by poor drainage as a result of the macro texture, and is regarded as water of a depth greater than 3 mm.

A case in point is the relatively higher value for the TWI as shown in figs. 5 and 6 below. Higher values represent drainage depressions, lower values represent crests and ridges as can be identified from the raster resolution (in this case 1m x 1m; 4 points.m-1).

Figure 5: Higher indices obtained over TWA A towards entry to Runway 31.

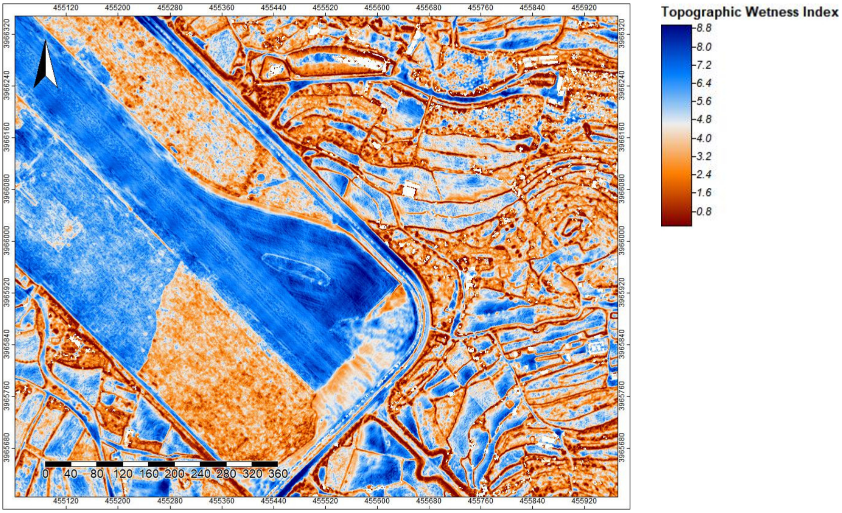


Figure 6: Spatial distribution of the wetness index over Apron 9, in front of terminal building, but towards air side at Malta Luqa Airport.

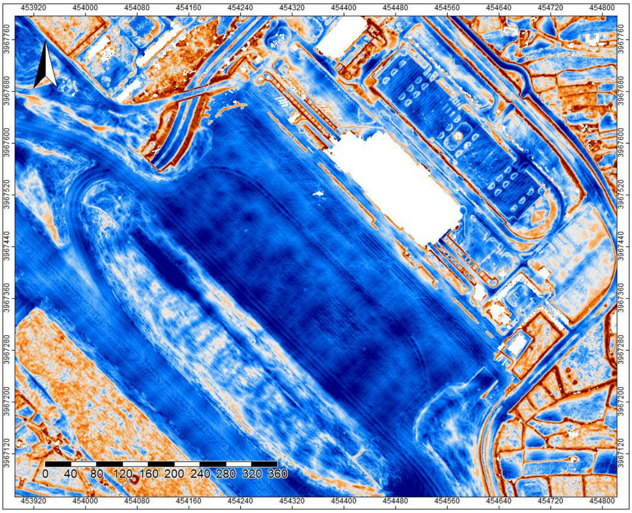
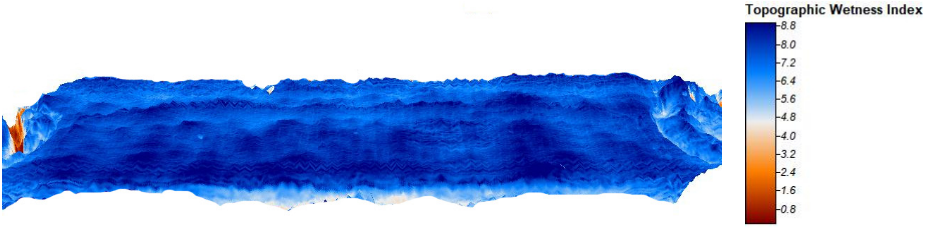


Figure 7 shows a shallow 3D profile of Apron 9 to illustrate the unevenness of this part of the airfield at the time of data acquisition. Areas that appear dark blue have a higher wetness index, which can be translated to deeper depressions within the Apron's surface. Topographic raster data analysis can also easily extract transverse and/or longitudinal profiles to quantify unevenness in both axes (not shown).

Figure 7: 3D profile of the topographic wetness index of Apron 9 as seen from the side.



Other potentially problematic areas within the airfield were identified, including (i) parts of RWY 05 (such as at 451508.302 m E; 3967507.633 m N; 451425.361 m E, 3967646.245 m N), (ii) exit of TWY F onto runway (453753.366 m E, 3967667.832 m N) and (iii) junctions of TWY D onto both runway and Apron 9. These areas could potentially lead to wet surfaces or the occurrence of water patches (standing water). Although these problematic areas were confirmed on the basis of experience, actual onsite verification and measurements are strongly recommended, especially during high rainfall rates.

Since the time of collection of the LiDAR data in 2012, important structural improvements have been made to Apron 9, and new tarmac resurfacing of its sides, including in taxiways have been carried out. The Airport Management has meanwhile upgraded the assessment of the runway water surface conditions by introducing runway flood sensors based on ICAO recommendations. These sensors collect real-time rainfall measurements to establish the runway surface conditions, especially during and after heavy rainfall episodes.

Study limitations

This study does not look at the link between rainfall rate, drainage and texture capacity of the airfield pavement. It merely highlights the fundamental aspects of the first two variables namely – rainfall rate (and return period of extreme events) as well as problematic areas of the airport pavement that might pose problems with water drainage and resulting contamination. Moreover, local rain intensity has been derived from a single rain gauge station located along a Luqa runway and does not provide a precise rainfall rate along different parts of the runway.

Recommendations

Further studies to link rainfall rate with roughness and surface drainage capacity is hereby being recommended in order to establish critical thresholds, which could then become incorporated in risk management protocols for the runway. Parts of the Luqa runway can be subsequently classified based on different drainage characteristics until further improvements to lower risks of hydroplaning are made. The following recommendations are being put forward:

- A number of water depth modelling studies can be carried out (see Benedetto, 2002) that can help managers define timely thresholds of relevance to ATC and flight crews regarding the amount of water present on a runway.
- The Weather radar information available at the Malta Airport MetOffice can be used to assist in this timely warning. However, this is a subject that needs further study.
- Calculate in real time, the safety condition of each landing or taking off, on the basis of runway surface flood water measurements and related conditions.
- Use the climatological information gathered by this study as thresholds of expected critical rainfall events that could make the airport unsafe and include this climatology as part of the safety management of airport pavement.
- The introduction of new measurement and communication technologies on the runway can make possible data gathering and information processing related to the degree of wetness of the runway. This information could be then transmitted instantaneously to all parties concerned such as flight crew, ATC and Meteorological Office. Such a system should also be capable of ATIS integration, thus eliminating weak points of communication through ATC.
- Conduct periodic LiDAR surveys and calculate the spatial topographic wetness index of the airport pavement to assess in a holistic and quick way, the state of unevenness of the runway and to highlight problematic areas without delay.

Conclusion

When an aircraft lands and brakes on a wet runway, the skid resistance drastically decreases under such conditions since the action of braking it strongly dependent on the depth of the water layer residing over the runway at that point in time. Moreover, the loss of contact between the tire and the pavement increases with aircraft speed, which can extrapolate to a zero-friction force, especially during takeoff. These are two of the most critical aircraft maneuvering on the runway.

From both weather and climatology point of view, rainstorm intensity is statistically correlated to the rainstorm duration and to the return period at the site of observation. This study illustrates these two events for Malta Luqa Airport, in terms of absolute values and return periods, within a hazard analyses framework for the Airport. In this sense the return period of particular hazards plays a fundamental role for Airport safety management.

Moreover, this study provides excellent insight on the exposure of local runway infrastructure to wet/flooded conditions due to climatic conditions with all the more reason to assure proper water drainage on the runways.

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