Modelling of water flow and prediction of water depth on runways

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Abstract

Runway friction capability may be greatly reduced in the presence of water. High water depth can cause aquaplaning, reducing friction to near-zero. To ensure safe aircraft landing or take-off, information about runway surface condition has to be delivered to flight crews, in terms relevant for aircraft performances. Aircraft braking performances when water is present on the runway are assessed through water depth and surface covered. However, assessing depth and percentage coverage of water on the whole length and width of a runway is a huge issue due to the lack of tools and methods, and the rapidity of rain evolution and water flow. This paper presents a method and a tool developed for optimising the runway condition monitoring. Based on road experience, the project aims at modelling the water flow on runway from its geometric and surface characteristics and to predict water depth during rainy events. The developed tool is designed to alert runway inspectors about the time and place where water accumulation becomes dangerous.

Keywords: Aircraft operationnal performances ; runway surface conditions ; water ; flow ; water flow model ; runway characteristics ; slope ; macrotexture ; microtexture

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Résumé

L'adhérence des pistes aéronautiques peut être fortement réduite en présence d'eau. De fortes hauteurs d'eau peuvent provoquer l'aquaplanage, réduisant l'adhérence à zéro. Afin de garantir la sécurité des opérations aériennes, les équipages doivent être informés de l'état de surface des pistes. En présence d'eau, les performances des avions sont calculées à partir de la hauteur d'eau et la surface contaminée. Cependant, évaluer une hauteur d'eau et une surface contaminée sur toute la longueur et la largeur de la piste est particulièrement délicat en raison de l'absence d'outils et de méthodes, mais également de la rapidité de l'évolution du phénomène. Cet article présente une méthode et un outil développé pour répondre à cette difficulté. Un modèle routier a été adapté afin de modéliser les lignes d'écoulement sur une piste à partir de ses caractéristiques géométriques et de surface, et de prédire les hauteurs d'eau pendant les épisodes pluvieux. L'outil développé dans le cadre de ce projet permet d'alerter le superviseur de piste sur le moment et le lieu où l'accumulation d'eau devient dangereuse.

Mots-clé: Performances opérationnelles des avions ; état de surface des pistes ; eau ; écoulement ; écoulement d'eau ; caractéristiques des pistes ; pente ; macrotexture ; microtexture

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1. Introduction

Aircraft operational performances, at landing or take-off, are strongly dependant on runway surface conditions, which may be severely degraded during adverse weather conditions. When such events appear, methods and means must be implemented to characterize runway surface condition and to provide pilots with relevant information about how well the surface will perform. The case of water contaminated runways is apart from other types of contamination. Indeed, rain is a usual phenomenon and perception of danger is lower compared to snow- or ice-conditions. As a consequence, less attention is paid to wet or water contaminated runways and more accidents or incidents occur on wet or water-contaminated runways than on snow- or ice-contaminated runways.

Van Es (2005) performed a statistical analysis of 35 years of landing overrun accidents, from the data of National Aerospace Laboratory (NLR) Air Safety Database. This database contains detailed information about worldwide aircraft accidents and incidents since 1960. More than 40.000 accidents and serious incidents are documented: airport data, flight data, weather data, fleet data… This database is built on official reporting systems, insurance claims, accident investigation boards, aircraft manufacturers, civil aviation authorities. Data sample is based on the following criteria: landing overruns, only accidents, no unlawful or military action, fixed wing aircraft with a maximum take-off weight greater than 5.500 kg, occurred between 1970 and 2004. 400 landing overruns have been identified and analysed. This study showed that 47.8 % of runway overrun occurred on a wet or flooded runways, while only 5.5 % occurred on Ice/Snow/Slush contaminated runways. Once corrected from the number of flight, data show landing overrun accident risks increased by ten on wet or water contaminated runways, compared to dry runways.

This paper deals with the estimation of waterdepth on runway to help pilot during take-off and landing. First part of the paper is a brief state-of-art concerning water depth measurements and water flow modelling. The second part describes the developed approach. Then, the validation protocol is presented and finally results are presented and discussed. Perspectives to improve the model are drawn in the conclusion.

2. Context

2.1. Problem statement

Friction capability between tire and the runway may be severely degraded in the presence of water. A direct consequence is the decrease of control and braking capacity of aircraft when take-off and landing. Safety of aircraft operations would be improved by a better estimation of water depth on the runway during rainy events. Water depth depends on runway geometrical and surface characteristics (such as slopes, evenness, texture…) and meteorological parameters (rain intensity…).

Based on rain duration and intensity, four sequences of pavement wetting may be distinguished (Petrazek, 1975) (Watkins, 1964):

1. First, water is stocked into inter-aggregates spaces (texture), until the pavement capacity storage is reached,
2. Then, water flow starts, and flow rate increases until an equilibrium is established,
3. Once rain stops, water flow rate decreases until zero value. At this point, pavement texture still stores part of water,
4. Finally, stored water decreases due to traffic or evaporation.

Water depths are generally assessed through visual observations, or using simple tools such as dipsticks. These methods are inaccurate and time-consuming. They are not compatible with airport capacity requirements, with size of monitored surfaces, or even with rapid evolution of rainy events. Finally, airport operators and pilots may not be confident in the resulting information. That is why another approach is looked for. This approach is based on the use of a model. It should allow real-time information, a complete runway surface monitoring, and anticipation of runway surface condition.

Modelling of water depth on the runway implies several factors, especially runway surface characteristics. In road field, several models to estimate water depth have been developed and in-lab validated: Moore (1975), Ivey (1975), Gallaway (1979), VERT (2001) and Do & Kane (2010).

However, such model does not exist for runways. This paper aims at adapting and evaluating one road-developed model for runway in real and non-controlled meteorological conditions. The model relates rain intensity to a resulting water depth on the runway, using runway geometric and surface characteristics, and rain intensity. The final goal is to improve the monitoring of runway surface conditions by helping the runway inspector to choose best-timing for runway inspections. It alerts about the time and place where water accumulations become dangerous.

2.2. Adopted solution: diagnosis and estimation of water depth

The adopted solution for the diagnosis and estimation of water depth on runways is illustrated in Figure 1.

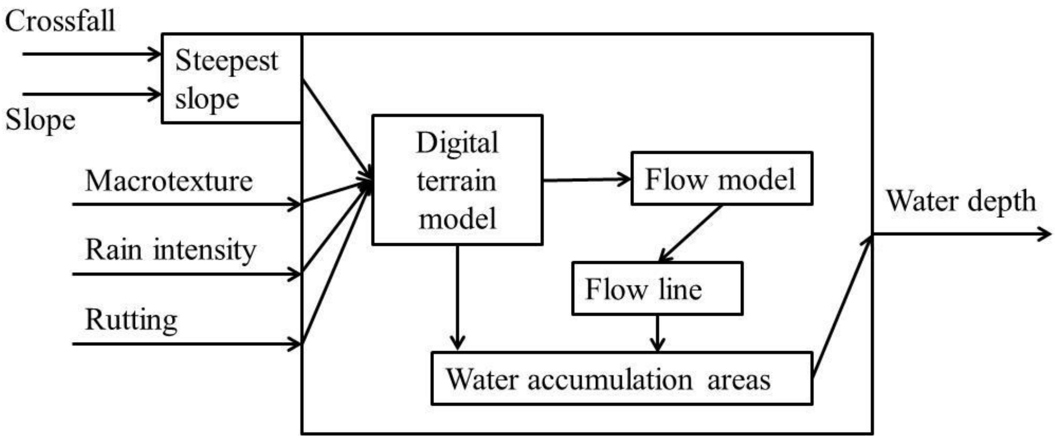

Figure 1: Algorithm for water accumulation areas identification and water depth assessment

This solution has initially been developed by the Centre d'Etudes Techniques de l'Equipement (CETE) de Lyon (Gothié&Pruvost, 2001), (Guillevicet al. 2006) to identify water accumulation areas on road network and to prevent aquaplaning. Aquaplaning is directly related to the presence of water on the pavement, worsened by high water depth. The hydrodynamic pressure on the leading edges of road asperities tends to lift up the tyre and to diminish the footprint area until a total loss of contact, which implies a total loss of friction. Aquaplaning is also an issue for aircraft. It is even more critical for aircraft because car-drivers can and have to reduce speed to adapt to encountered and seen situation. Aircraft pilots cannot and therefore have to pre-set aircraft from information got from the ground. Aircraft settings are different if the runway is wet, or covered with standing water, and depending on the depth of water.

This simplified approach, presented in Figure 1, has been adjusted and adapted to runways. Based on geometric runway characteristics, a numerical mapping has been generated. The runway has been spatially meshed into simple rectangular elements. Lines of steepest slope have been calculated from geometric relations. Water flow lines are merged with lines of steepest slope. Once these parameters have been determined, water accumulation areas are identified and the water depths are calculated. Meteorological data are used either from weather-station observations or from forecasts. Use of forecasts allows predicting the quantity of water on the runway and to anticipate runway surface condition to short or medium term.

3. Determination of water depth on runways

Previous works have emphasized numerous factors influence wetting and drying of pavement surfaces. These are related to meteorological conditions (rain intensity, wind, humidity, temperature,…), to runway characteristics (water flow lines, ruts, texture…) and traffic (speed, number of movements…). Every obstacle blocking water flow will extend wetting duration. Some factors are taken into account in this study.

This part presents fundamental parameters and the mathematical model.

3.1. Determination of water flow on runway

The runway is split up into n elementary elements (2D spatial meshing) to:

- Calculate the steepest slope vector on each element (flow way),
- Determine flow line length on each element and on the runway (Figure 2)

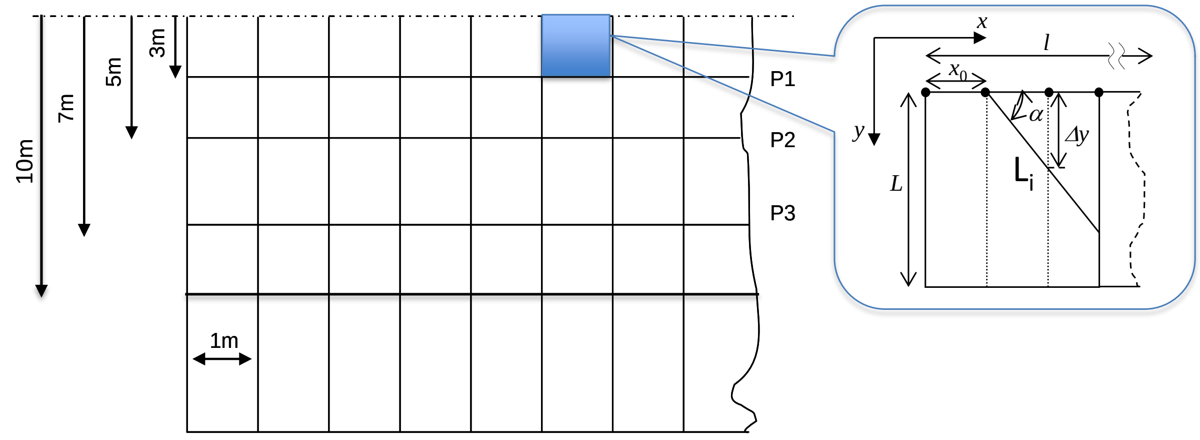

Figure 2: Spatial meshing and determination of flow line on element $n_{i,j}$

The resultant vector of longitudinal and lateral slopes is plotted, starting from the highest element. This vector determines the line of the steepest slope and the direction of the flow line according to an angle α with the centre line. Three cases are considered for the calculation of flow lines (Figure 2). These are:

$$1.\quad \Delta y + y_0 > L_i \;=>\begin{cases} x_1 = \dfrac{L_i - y_0}{tan\,(\alpha)} + x_0 \\ y_1 = L_i \end{cases} \tag{1}$$

$$2.\quad \Delta y + y_0 < L_i \;=>\begin{cases} x_1 = l \\ y_1 = tan(\alpha)(l - x_0) + y_0 \end{cases} \tag{2}$$

$$3.\quad \Delta y + y_0 = L_i \;=>\begin{cases} x_1 = l \\ y_1 = L_i \end{cases} \tag{3}$$

Where (x_0,y_0) are entry coordinates (coordinates of the highest point of the flow lines, where the line begins), (x_1,y_1) are exit coordinates (coordinates of the flow line intersection with the edges of the element), and L_i is the length of the flow line. x_0, y_0, x_1, y_1 and L_i are expressed in m.

The case of a perfectly plan element, having neither a longitudinal nor a transversal slope, can be imagined. This case is excluded because:

- The flow is non-uniform and the direction is random,
- Road and runway pavements are constructed with slopes, and
- A flow line of zero or infinite length is theoretically impossible.

In order to ensure the continuity of element $n_{i,j}$ flow line, it is extended by adjacent elements ($n_{i+1,j}$, $n_{i+1,j+1}$, $n_{i,j+1}$) flow line as showed in Figure 3. The water depth calculated at the exit point of each element is assigned to the entry point of adjacent element, and so on until the flow line exit the runway.

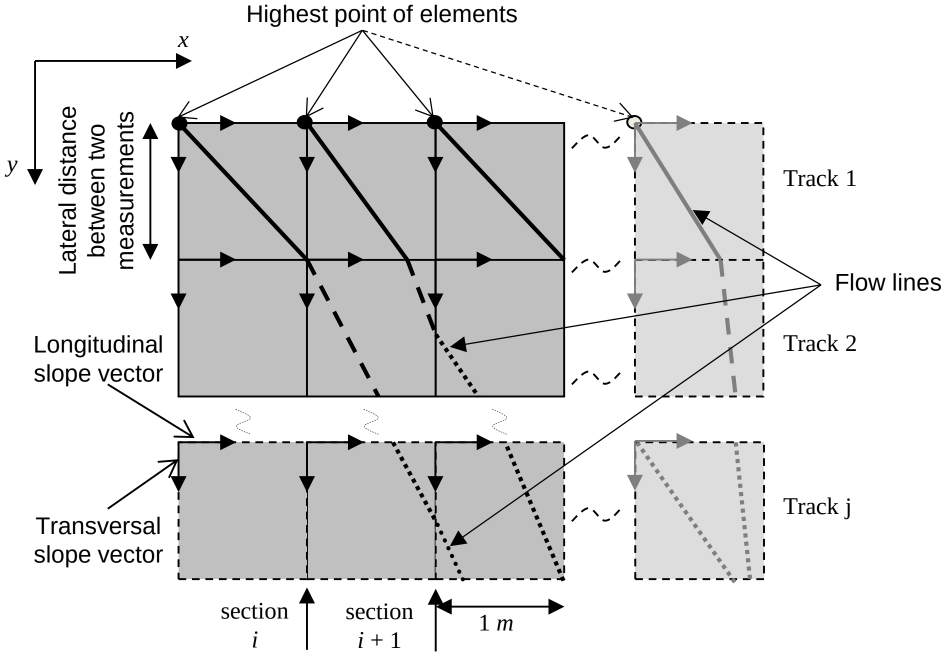

Figure 3: Principles of determination of flow line on a runway

Elements can be crossed by one or several flow lines. As a convention, the water depth at the element surface is equal to the highest value resulting from each flow line crossing the element. The total length of the different flow lines is determined each one meter on the runway. The water film thickness calculus is based on the assumption that the amount of water everywhere on the runway is the sum of the water due to rainfall intensity and to the water accumulation along the flow lines.

3.2. Retained model for water depth on runway

This part presents an adaptation of the model used for road infrastructure (Vert, 2001). It is based on an elementary model, completed and improved through in-situ experiments. This model allows characterizing water depth on the runway taking into account macrotexture and measurement uncertainties. The mathematical relation defining this model is (Gothié&Pruvost, 2001), where macrotexture descriptor is updated following (ISO, 1997):

$$w = 0{,}29\, MPD^{0,4}\, \frac{(I\, L)^{0,4}}{p^{0,3}} - 1{,}1 MPD + 0{,}30 \qquad (4)$$

Where w, I, L, p and MPD are respectively, water depth (mm), rain intensity (mm/h), flow line length (m), slope (%) and macrotexture (mm)

On-site observations, a proper choice of reference water depth (above which flow starts) and repeatability of experimental measurements, made possible a precise identification of the model coefficients.

Pavement deformations in the short wavelength (ponding…), characterised by megatexture, have been taken into account in a first approach. The resulting water depth, w_1 (mm), is given by the following equation:

$$w_1 = 10^{((L_{me}/20)-5{,}8)} + w \qquad (5)$$

whereL_{me} is the indicator of megatexture (dB) calculated as in International Standard ISO 13473-1 (ISO, 1997).

4. Experimental validation

In order to evaluate the developed approach, results from the model will be compared with on-site measurements during rainy events. Data are extracted from the developed calculation tool on the one hand, and from real on-site measurements on the other hand. Geometric and surface characteristics data have been acquired from the

VANI (Véhiculed'ANalysed'Itinéraires) vehicle (Cerezo et al., 2011), water depth measurements from a water depth sensor, and rain intensity data from the weather station. This part presents the test site and experimental plan for data collection.

4.1. Test site: runway 18L/36R of Lyon-Saint Exupéry airport

The test runway used for the validation of this approach is the runway 18L/36R of Lyon-Saint Exupéryairport (Figure 4). It has three taxiways and one high speed turn off taxiway. It is 2670 m long and 45 m wide. Figure 4 also shows measurement points retained for the experimental validation.

Figure 4: Runway 18L/36R of Lyon-Saint Exupéry airport

4.2. Runway geometric and surface characteristics

Geometric and surface characteristics have been measured in October 2012 using the VANI device from the CETE de Lyon (Figure 5). This device provides curves radius, slopes, crossfall with a one meter step, and surface characteristics (macrotexture and evenness in short wavelength with a one meter step).

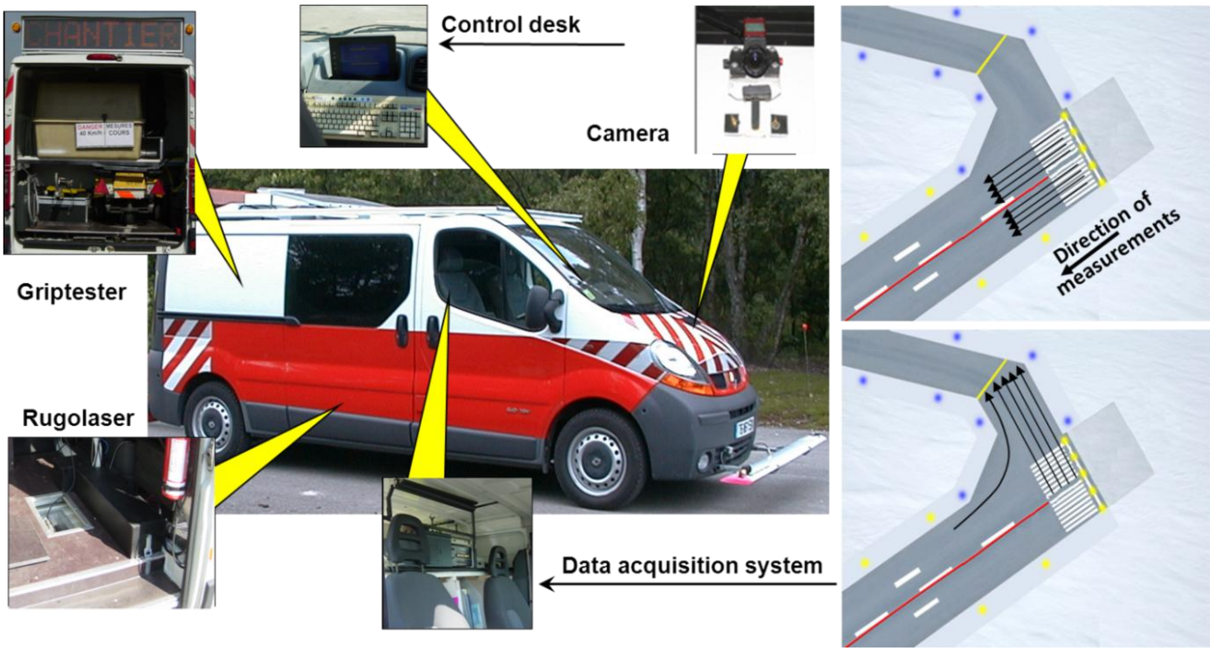

Figure 5: Véhicule d'ANalyse des Itinéraires (VANI)

In order to cover the whole width of the runway, nine measurements lines have been realised of which one on the centre line. These lines are 3, 5, 7 and 10 m away from the centre line (Figures 4 and 5). Five measurement lines have been realised on the taxiways, including one in the curves to determine the curve radius.

4.3. Water depth measurements

Water depths are measured using a sensor VAISALA (VAISALA, 2011) of type DSC111 (Figure 6), mounted on an airport vehicle. It is an optical sensor functioning on a spectroscopic principle. According to its technical sheet, it can identify runway surface condition (dry/damp/wet) and detect water depth from 0 to 2 mm with a resolution of ±0,01 mm. Above 2 mm water depth, the error is about 5 to 7 %, which is acceptable compared to other water depth sensors.

Figure 6: VAISALA sensors and its setting constraints

Water depth measurements are localised using a GPS SX Blue II, delivering a sub-meter positioning. It has been installed and synchronised with the VAISALA sensor. Data acquisition and storage are carried out by an on-board computer. Data collection started in October 2013.

4.4. Meteorological data

Meteorological data are obtained from an airport weather station: rain intensity, ground and air temperatures, wind speed and direction are recorded on a 6 minutes step. They are measured using a pluviometer, a thermo-hygrometer, and an anemometer. Figure 7 shows an example of rain intensity in mm recorded by Meteo-France.

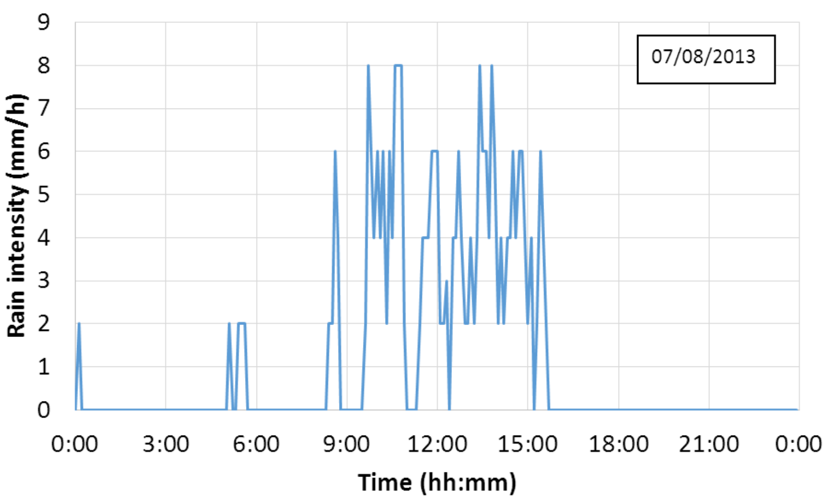

Figure 7: Example of rain intensityrecorded by Meteo-France

5. Results and discussion

The entry/exit interface of the calculation tool is programmed using the Delphi software. An example of the interface is showed in Figure 8. Figure 8 is a georeferenced map of one 80 m long section of runway 18L/36R. It shows for the whole section width and length the water depth on each meshed element. User can click on one element to have the calculated water depth value at this precise point.

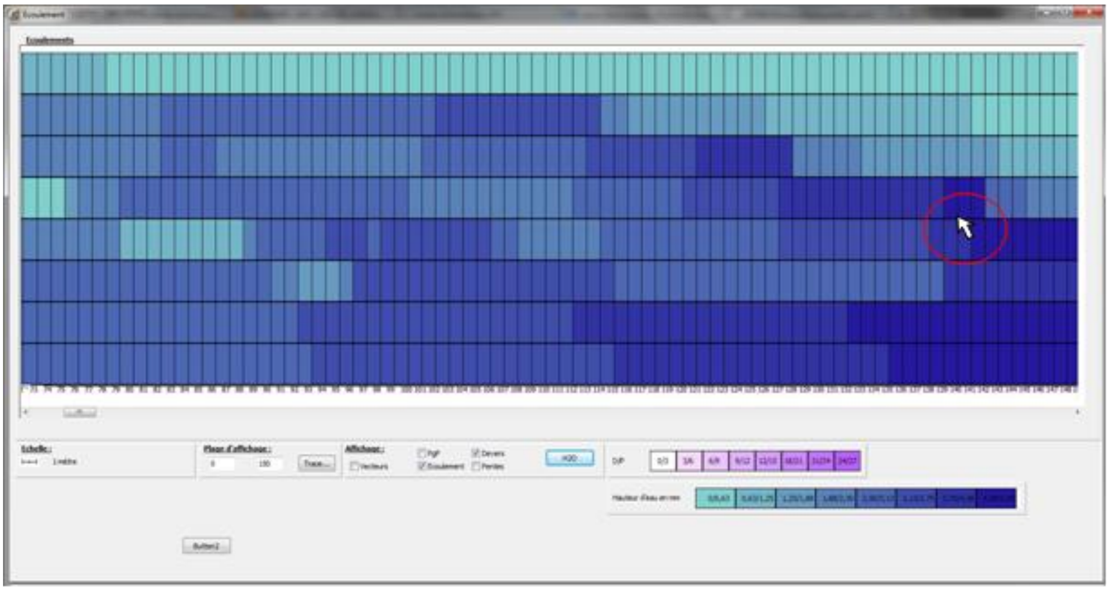

Figure 8: Calculation interface (presentation of water depth)

Results can be graphically visualised on the window. They can be plotted according to any line parallel to the x or y axis. Results can also be visualised as surface function of x and y. Three displays are possible:

- Direction of steepest slope lines,
- Flow lines,
- Water accumulation areas and water depth (Figure 8).

Comparative tests have been undertakento validate the approach. It consists in comparing water depth calculated from equation (5) and those measured in-situ in real time with the sensor. Figure 9 shows a good consistency of water depth values from both the model and the measurements.

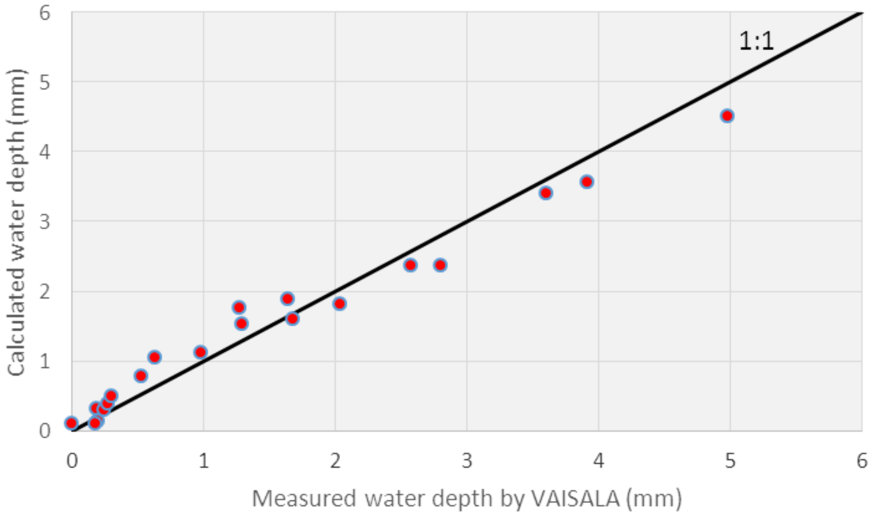

Figure 9: Comparison of calculatedand measured water depth

After removing outliers (data outside of VANI measured area), figure 9 shows the model prediction are satisfactory. A mean error of 8 % for low water depths and 19 % for high water depths has been calculated. These errors may be explained by:

1. Errors of water depth measurements using the VAISALA sensor,
2. Errors of GPS positioning under overcast sky, despite a careful experimental protocol (longer acquisition time),
3. Errors of the macrotexture modelling: indeed, the water storage capacity has been assumed to be equal to the mean profile depth, but the real water storage capacity differsfrom one area to the other.

These preliminary results still have to be confirmed by a greater number of observations. Experiment will go on during 2014 to get enough data to consolidate these conclusions.

6. Conclusions

This work has been carried out as part of Civil Aviation Technical Center (STAC) research works about the characterisation of runway surface condition under adverse weather conditions. It aimed at implementing a predictive model for water depth on runway during rainy events. These predictions can be used by airport operators to adapt their runway monitoring strategy. The prediction of water depth is based on pavement characteristics (slopes, evenness, texture…) and water flow equations. A validation protocol has been developed and is now implemented. First results are very encouraging, and validation work will go on in 2014 with the goal of obtaining about 100 measurements.

Research work will also be pursued. Drying phenomenon will be modelled and added to take into account other relevant meteorological parameters such as wind, temperature and air relative humidity. This improvement will make water depth predictions even more precise.

A better knowledge of water depth on the runway and runway surface characteristics open the way to a better characterisation of runway conditions. Using an appropriate aircraft braking modelling, this work could be used as a solid ground for a prediction of friction coefficient representative of aircraft performances.

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