The impact of drainage on terrain UGV movement

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Abstract. The drainage (hydrosphere) is one of the main elements determining the military vehicles mobility. The grade of this determination is given by width, gradient, depth and qualitative parameters of drainage on overall forms of its occurrence. The goal of this paper is the identification of main geographical factors and parameters of drainage that affect the modelling of cross-country movement. In paper are included some classifications of overall coverages of terrain by a drainage, drainage structure, characteristics of watercourse banks, watercourse width, depth of watercourses and water expenses, character of a bottom, water flow rate and flow speed, climatic effects and mutual position of drainage and other geographical subjects.

1. Introduction

The drainage (hydrosphere) is one of the main elements determining the troops movement on terrain first off by spatially distribution of landscape sphere to partial units, there through it is influential both in the entire system of military operations and movement of particular vehicles. The complex influence of geographic and meteorological factors on the drainage cross ability by a terrain vehicle has not yet been described theoretically and practically in the world literature. Several partial theoretical knowledge and practical experience were publish in [1-6].

The grade of this determination is given by a specific hydrologic area and the slope gradient, depth and qualitative parameters of drainage on overall forms of its occurrence. The basic form having influence on vehicle traffic ability is surface water, which we can classify from dynamic aspects of running and standing water.

With regard to the other elements of traffic ability, drainage has dynamic character rising from changes of its attributes given above all by meteorological conditions (e.g. precipitation, temperature), by behaviour of subterranean waters (affecting hydrological transformation of waters), by terrain relief (slope characteristics of watersides, bottom surface) – see also [5], [7], [8] by human capability to affect these attributes (e.g. by control of water level and flowage by use of dam reservoirs, by engineer works).

The evaluation of dynamic changes of particular parameters of drainage traffic ability in real time is not possible just by exploitation of databases or map data, but that evaluation presupposes elaboration of complicated models encompassing data gathering system and evaluation of conditional (meteorological, hydrological and other) data and, on the basis of these data we can modify long-term statistical parameters of drainage and implement them in models of traffic ability see also [5], [9-15].

The evaluation of drainage traffic ability can be made by various criteria given by level of command, combat branch, transport techniques used etc.

The main focus of this paper was the theoretical analysis and also the practical evaluation of the drainage impact on Cross-Country Movement (CCM) using the topographical and hydrological data.
and the tachymetry and hydrometric measurement methods on the selected river profile of watercourse.

2. Factors affecting the ability of a vehicle to cross drainage
Basic factors affecting drainage traffic ability are: overall covering of terrain by drainage, drainage structure, characteristics of banks of water expenses and watercourses, watercourse width, depth of watercourses and water expenses, character of a bottom, water flow rate and flow speed, climatic effects, mutual position of a drainage and other geographical subjects. The abovementioned factors are subjects of changes (depth, width and flow speed at particular).

2.1. Overall covering of terrain by a drainage
The overall covering of terrain by drainage can be expressed by absolute number in square unit given (e.g. in km²) or by coefficient of drainage cover of terrain \( K_{VO} \) (ratio of common surface of standing and running waters \( P_{VO} \) to total surface of terrain of interest \( P_{CE} \)) – see also [16], [17]:

\[
K_{VO} = \frac{P_{VO}}{P_{CE}}
\]

Important factor of drainage density characterizes total level of line obstacles of drainage from the point of view of terrain traffic ability.

2.2. Drainage structure
Drainage structure is given by: mutual relative position and distances of water expenses and watercourses, size of particular water expenses and watercourses, form of drainage and orientation of particular water expenses and watercourses with respect to presupposed direction of movement. Mutual relative position and distance of particular drainage subjects has the impact on throughput of moving units of troops (mobile techniques at particular) in time available and depends on directions of troops movement see also [18], [19].

Size of particular water surfaces and watercourses is given by expense of standing water and by length respectively by width (at great rivers) of watercourses, water ports and waterways. The extent of individual water expenses is expressible by number of hectares, eventually of km².

Traffic ability of an area that includes water expenses depends both on drainage extent (surface, length) and on size and structure of moving units of troops. It is true, that the bigger unit of troops is and the wider is the strip of movement, the better is its technical equipment for overcoming a water obstacle and, simultaneously as a rule the bigger are considered values of drainage criteria that are limitative for purpose of troop’s movement.

Forms of drainage and orientation of particular water expenses and watercourses mostly affect the directions of movement. Drainage form is given by course of bank lines and axes of watercourses and it is characterized by crookedness (tortuosity) \( K \), expressible by ratio of bending line length \( D_k \) to direct join of end points of watercourse (bank section of water expense) \( D_p \):

\[
K = \frac{D_k}{D_p} \geq 1
\]

Typical example of complex shape of drainage is meander watercourse that has meander lobes of the length exceeding semicircle (\( K > 1.57 \)). Form of drainage area is expressible by coefficient of basin form

\[
K_{TP} = \frac{P}{L^2}
\]

where \( P \) is a basin surface in km² and \( L \) is length of valley bottom line in km. If:

- \( K_{TP} = (0.07; 0.24) \)… a basin is classified as elongated;
- \( K_{TP} = (0.25; 0.50) \)… a basin is classified as flabellate.
2.3. Characteristics of watercourses banks and water expense banks

Particular characteristics of the abovementioned hydrological features are chiefly forms and inclinations of watercourses and water expenses methodically soluble the same way as terrain gradient elements and elements of micro relief. Those characteristics are also connected with width and depth of watercourses and water expenses.

Civil engineer works made on watercourses and water expenses are important parameters too.

It is necessary to observe the following principles to organize deep fording places as is stated in [20] according to the terrain testes:

- steepness of water entryway can be in summer 25° and in winter 15°;
- steepness of the bank moving out: in summer 15° and in winter 10°.

Organizing wade (ford), we have to make up the inclination of both banks:

- for wheeled vehicles to 8 - 10% (5 - 6°);
- for track type vehicles to 15 - 20% (9 - 11°).

2.4. Watercourse width

Watercourse width is related to profile determined by distance (in km) from estuary up the stream. A width is determined in relation to mean level of “n-year recurrence flood” (respectively to watershed at terrain level). Its significance is relative and depends on technical parameters of combat vehicles of troops and on special equipment for the needs of water crossing the troops can manage (engine crossing assets and techniques at particular).

The width of watercourses is the parameter which is over time varying and depends on both climatic conditions, particularly on precipitation pattern, and on watershed profile, i.e. on its height, width and incline relations.

To determine the critical values of watercourse width for purpose of its passing by military vehicles, for an unknown area, we can partially start from results of the Earth remote sensing analysis.

2.5. Depth of watercourses and water expenses

The depth of watercourses and water expenses is very changeable. The depth depends on precipitations, flow pattern, i.e. on stability of water sources, on watershed profile, flow speed and character of bottom. The depths of streams, torrents and little rivers come up to 1m rarely. Depth of most rivers varies from values lower than 1 meter up to several meters. At higher water level, the depth rises, water escapes from banks and floods the circumambience.

To determine critical values of watershed depth for purpose of its passing by military vehicles, we can in a rough way to use Table 1.

Table 1. The most permissible depths for wading according to [20].

| Units/ Equipment                        | Permissible depth of watering at flow speed |
|----------------------------------------|-------------------------------------------|
|                                        | Up to 1 ms⁻¹ | Up to 2 ms⁻¹ | over 2 ms⁻¹ |
| Motorized infantry units – by foot 1.00|              |              |             |
|                                        | 1.00         | 0.80         | 0.60        |
| Automobiles: passenger GAZ-69 A        |              |              |             |
| truck 1.5t up to 2t                     | 0.60         | 0.50         | 0.40        |
| truck 3t up to 3.5t                     | 0.80         | 0.70         | 0.60        |
| truck 5t                               | 0.90         | 0.80         | 0.70        |
| Armored personnel carriers              | 0.70         | 0.60         | 0.50        |
| Truck-drawn artillery can pass the same depth as trucks | | | |
| Artillery drawn by full tracks:         | 1.00         | 0.90         | 0.80        |
| Tanks medium                            | 1.20         | 1.10         | 1.00        |
| heavy                                  | 1.50         | 1.40         | 1.30        |

Missilery can pass the same depth as towing vehicle (carrier)
### 2.6. Character of bottom

Character of a bottom depends on layers of underbed of watershed, on the bottom sediment runoff, i.e. on the material (shingle, sand, mud and bottom scour) pushed or towed by stream longways in direction of bed slope. Intensity of these dislocations and thickness of bottom scour are dependable on the bed slope, quantity of water and flow speed. If a watercourse has a muddy bottom, even a shallow river constitutes hardly passable obstacle.

### 2.7. Water flow rate and flow speed

A watercourse pattern is characterized by flow of water and flow speed.

*Flow speed* depends on water quantity, bed slope, watershed profile, bank roughness and quantity of a bottom scour and suspended load.

Mean speed of flow $v$ is quantity given at meters per second and is determined as arithmetic mean of partial speeds measured at various places of cross profile of a river. Measurements are made e.g. by use of hydrometric wing rotating in water flow. The speed of flow at position of cross profile given is calculated from number of revolutions per time unit. In the hydrological practice, providing stable flow of water, we can express mean profile speed as follows:

$$v = C \sqrt{RI}$$

(4)

where

- Chézy’s factor $C = \frac{1}{n} R^{\frac{1}{6}}$, where $n = (0.020; 0.050)$ is the coefficient of roughness;
- hydraulic radius $R = \frac{F}{O}$, where $F$ is flow section line surface, $O$ is wetted perimeter of watershed;
- longitudinal inclination of level $I$.

By the crossing of a watercourse, we have to consider that the flow speed at different points of a river is not constant. The lines joining points with equal speed follow approximately the cross section line of the watershed bottom. The speed of flow has the highest value at direct sections upon the deepest point at the centre of flow profile just below the water level and decreases in direction to banks and bottom. The line joining points with maximum speed is stream contour line. Mean speed on the entire flow profile is about 30% lower than the speed measured in stream contour line.

The speed of flow measured in mountain gills is $5 - 7 \text{ ms}^{-1}$, at floods up to $12 \text{ ms}^{-1}$. The speed of flow of lowland watercourses varies from $0.5$ up to $1.5 \text{ ms}^{-1}$. The flow speed rises at high water level and floods up to $3 \text{ ms}^{-1}$ and even more. To evaluate the pattern of watercourse, we have to determine the movement of water at given section, which we have to pass over. At steady-state motion in profile given, the speed of flow is stable and constant. At sections where the cross profile or the watershed inclination are variable, the flow speed is unequal and unstable.

To evaluate water level and its changes, there are stream gauging stations. They are placed so they can obtain the best possible realistic characteristics of watercourse pattern. Stream gauging stations at important places are fitted with recording devices (limnigraphs) to record continuous changes of water level in time. For the determination of critical flow speed of watercourse to pass it by military vehicles we can use the data contained in table 1.

*Water flow rate* belongs to the most important hydrological characteristics. A water flow is presented in $\text{m}^3 \text{s}^{-1}$. It can be calculated e.g. as the product

$$Q = k_1 S v_p$$

(5)

where

- $k_1$ is reducing coefficient from hydrometrical measurements of profile (section line) given; if it is unknown, then e.g. values $k_1 = (0.55; 0.85)$ are valid in conditions of temperate zone;
- $S$ is surface of hydrometric profile of watershed;
• mean surface speed of a watercourse.
A water flow depends on a many parameters of drainage area of watercourse evaluated, primarily on:
• precipitation pattern;
• type of groundwater body (structure of rocks and soils of drainage area given);
• meteorological (climatic conditions) – see below;
• stream flow regulation of water reservoirs of drainage area given etc.

2.8. Climatic effects
Climatic factors affecting changeability of watercourses traffic ability are as follows:
• precipitation on drainage area given;
• temperature affecting water evaporation on given drainage area and traffic ability of standing water at first in winter season, when ice cover can to ease or decrease the grade of traffic ability significantly;
• speed, height and direction of winds affecting water evaporation on the entire drainage area;
• atmospheric pressure, water vapor tension etc.

2.9. Mutual position of drainage and other geographical subjects
Drainage traffic ability depends also on other subjects of terrain, particular on:
• overall surface and directional proportions of drainage and other subjects of a terrain;
• linkage to communications (number and parameters of bridges across watercourses and water expenses);
• relief (gradients of adjoining slopes, strength of banks, conditions for watering);
• character of rocks, soils, canopy and vegetation affecting drain parameters
• parameters of dam bodies on watercourses etc.

Presented parameters are basis for findings that we cannot rely on the abovementioned parameters to solve by itself but with use of comprehensive access to utilization with various levels of GIS data which can differentiate by the level of details, accuracy, quality, form or respectively by recentness if its contents.

3. Results and discussion
Actual traffic ability of a watercourse (water expense) at specific hydro-meteorological conditions is definable only in relation to a factual profile section where we determine actual values of coefficient $C_5$ according to relation:

$$C_5 = \prod_{i=1}^{6} C_{5i}, \quad i = 1...6$$  \hspace{1cm} (6)$$

where
• $C_5$ is deceleration coefficient of drainage factor;
• $C_{51}$ is deceleration coefficient of drainage sort factor;
• $C_{52}$ is deceleration coefficient of drainage depth factor;
• $C_{53}$ is deceleration coefficient of drainage width factor;
• $C_{54}$ is deceleration coefficient of drainage flow speed factor;
• $C_{55}$ is deceleration coefficient of drainage bottom characteristics factor;
• $C_{56}$ is deceleration coefficient of bank characteristics (bank gradient) factor.

The value $C_5$ depends on a great extent of capability of a particular vehicle to pass over water obstructions. Some vehicles are specially adapted to cross them after certain conversions e.g. by navigation or by deep fording (driving on the bottom) - tanks. On the contrary some vehicles have no special equipment. On the basis of evaluation of characteristics of particular water obstruction (factors $F_{51}$ to $F_{56}$), vehicle parameters and its adaptation to pass over an obstruction we obtain the value of deceleration coefficient $C_{51}$ (see table 2). Then we determine the deceleration coefficients $C_{52}$ to $C_{56}$
and in the end resulting estimation of value of deceleration coefficient $C_5$. The same principles as at the evaluation of coefficient $C_{s2}$ are used to evaluate coefficient $C_{s6}$.

**Table 2.** Determination of coefficient $C_{s1}$.

| $F_{s1}$                        | $C_{s1}$ |
|-------------------------------|----------|
| swamp, salt marsh             | 0        |
| watercourse, channel, waterway | 1        |
| pond, lake, water reservoir   | 1        |

It applies to relations:
- when $C_{s1} = 0$, then $C_5 = 0$;
- when $F_{s1}$ is a pond, dam, water reservoir, then $C_{s4} = 1$.

In the event of no occurrence of watercourse or water expense at section given, the value of coefficient $C_5$ equals to one. Presented parameters should be compared with technical specifications of vehicles relevant to water obstruction pass over (see table 1). To determine a vehicles capability to pass over water obstruction we can result from table 3 if we presuppose simultaneous influence of factors. While the particular factors in time succeed, these are to be considered separately one by one.

**Table 3.** Determination of traffic ability for mutual actuation factors.

| Traffic ability based on 1st factor | Traffic ability based on 2nd factor | Total traffic ability |
|------------------------------------|------------------------------------|-----------------------|
| Trafficable                        | Trafficable                        | Trafficable           |
| Trafficable                        | Hardly trafficable                 | Hardly trafficable    |
| Hardly trafficable                 | Hardly trafficable                 | Impassable            |
| Impassable                         | Trafficable, Hardly trafficable    | Impassable            |

3.1. Watercourses passability using UGV

Individual factors affecting the terrain passability using ordinary vehicles are the same for UGV. Therefore, all of the above mentioned findings can also be applied to the assessment of possibilities to cross watercourses using UGV (figure 1).

**Figure 1.** Overcoming water obstacle by SMSS. [21]

Figure 2. TAROS V2 6x6. Source: Archive of VOP Cz s. p., author: Radim Horák.

Methods of crossing a water barrier (fording, cruising) depends on the technical equipment of a particular UGV. Technical parameters that are limiting while assessing crossing watercourses result from construction characteristics of a particular UGV. Those are predominantly parameters as follows: fording depth, approach and departure angles, climbing capacity or other parameters. The table 4 shows technical parameters of selected UGVs.
Table 4. Technical parameters of selected UGVs.

| Type of vehicle       | MULE   | MATILDA             | TAROS (figure 2) | SMSS\(^a\) |
|-----------------------|--------|---------------------|------------------|------------|
| Variant               | XM1217 | Urban warrior, Block II, Scout | V2              |            |
| Weight (kg)           | 2,500  | 23.6                | 1,580            | 1,723      |
| Length (mm)           | 4,340  | 660                 | 2,870            | 3,680      |
| Width (mm)            | 2,243  | 508                 | 1,750            | 1,800      |
| Height (mm)           | 1,969  | 305                 | 1,565            | 2,150      |
| Speed (kmh\(^{-1}\)) | 65     | 3.22                | 25               | 38         |
| Suspension            | 6x6    | Tracked             | 6x6              | 6x6        |
| Main function         | Transport | Fighting, reconnaissance | Transport, reconnaissance | Transport, reconnaissance |
| Max climbing capability (°) | - | 50                 | 45               | 17         |
| Fording depth (m)     | 0.5    | 0.15                | 0.6              | 0.6        |

\(^a\) Squad Mission Support System

Watercourse information can be obtained from various data sources: DMR, topographic maps, satellite or aerial photography or others. The drawback of these data may consist in low resolution level, statistically processed data that do not have the informative value for a given phenomenon, or their relevance. These negative features are manifested most in hydrological characteristics of watercourses: flow velocity, flow rate, and water situation (depth). The actual hydrological data can be obtained from networks of water meter stations. Nevertheless, even the data obtained like that, cannot be used to evaluate the watercourse crossing along the entire watercourse.

Data collection for the assessment of options to cross watercourses can also be carried out directly in the field: geodetic data collection using contact as well as non-contact methods and hydrological data collection using the ADCP method (Acoustic Doppler Current Profiler), ultrasonic method (Flow Tracker) or using a hydrometer wing.

The assessment of a watercourse crossing using UGV is shown on the selected profile of the Třebůvka watercourse (see figure 3). The height profile (see figure 4) was measured using a tachymetry method with Leica TC 1500, and hydrological data using OTT MF pro (Handheld electromagnetic water flow meter with automatic discharge calculation). Compared to mechanical propellers, OTT MF pro can calculate the flow rate value automatically, store the recorded data in internal memory and, after that, export them in the text form. The velocity (figure 5) is measured using a magnetic-inductive method, and the depth using a diaphragm type sensor, which measures absolute pressure with one-point calibration.

Figure 3. Selected profile on the river Třebůvka in the municipality Mezihoří, author: Filip Dohnal.

Figure 4. Cross-section profile of the riverbed.
The assessment of crossing a watercourse in a specific section for a particular water situation consists in comparing technical parameters of vehicles from table 5 with measured values for a selected profile. This case analysis does not deal with other factors affecting the watercourse crossing as well (riverbank vegetation etc.).

**Table 5.** Measured parameters of a particular profile.

| Parameters                      | Value |
|---------------------------------|-------|
| Riverbed width (m)              | 15.71 |
| Flow width (m)                  | 5.80  |
| Medium depth (m)                | 0.55  |
| Average depth (m)               | 0.35  |
| Maximum depth (m)               | 0.51  |
| Left bank gradient (°)          | 27.90 |
| Right bank gradient (°)         | 26.10 |
| Medium flow velocity (ms⁻¹)     | 0.53  |
| Average flow velocity (ms⁻¹)    | 0.45  |
| Maximum flow velocity (ms⁻¹)    | 0.75  |
| Flow rate (m³s⁻¹)               | 1.70  |

Considering the technical parameter of the MULE vehicle, where only the fording depth can be evaluated, the permissible value is exceeded by 1 cm. With regard to sinking a vehicle in the bottom sediments, it is possible that limit value can be exceeded even more. Entering water in undesirable locations may cause irreversible damage or the vehicle may get stuck in the watercourse riverbed.

The UGV MATILDA is a much smaller vehicle than other selected ones in terms of technical parameters. Its fording depth is very small; therefore, it is a negative factor while assessing the passability of this watercourse profile. On the contrary, this vehicle is able to manage steep slopes efficiently. In case of a selected profile, the bank gradients reach lower values. Therefore, MATILDA is able to reach the water level and go back without major problems.

SMSS, whose fording depth is bigger than the assessed water level situation, is able to cross the watercourse riverbed. Its drawback consists in low climbing capacity which might result in overturning the vehicle while leaving the watercourse riverbed.

The TAROS V2 appears to be the only vehicle able to cross the profile. Parameters of the selected watercourse profile do not exceed the vehicle technical limits.

The assessment covering the watercourse crossing does not consider the assessment of crossing the terrain steps, evident from the height cross-section profile in figure 3, while entering and leaving the watercourse riverbed of the watercourse. These terrain steps reach approx. 0.5 m. Most vehicles have a predetermined permissible vertical obstacle value for a terrain step. By comparing a terrain step value and a vertical obstacle value of a specific vehicle, the possibilities of a watercourse crossing can further be assessed.
There cannot be forgotten the fact that surface characteristics (bottom surface as well as bank surface) may change after passing the first vehicle. Another vehicle that would cross the watercourse in the same location might get stuck due to worsened conditions. The adhesion coefficient on a tire contact with a wetted surface changes rapidly compared to a dry contact. In case of this profile, the riverbed bottom is gravely and should not cause major problems. On the other hand, a muddy bottom with a thick sediment layer or a rocky bottom with large boulders may result in getting a vehicle stuck in the watercourse (see figure 6).

![Figure 6](image)

**Figure 6.** Example of rocky deposits on the riverbed bottom and banks of the river Desná, author: Katerina Poulíčková.

4. Conclusion
The main objective of this article was to introduce the theoretical aspects of the influence of water on the movement of off-road vehicles and to verify these assumptions by practical terrain measurements. In the next period of research, the authors assume the use of a wider spectrum of data, i.e. hydrological data on river profiles (depth, flow rates), the use of a digital elevation model to determine the influence of the relief slope gradient on the velocity of a river flow, the data of river bottom sediment granularity and bearing capacity evaluation, etc. An important precondition for the success of the research is also the verification of the above mentioned methodology through terrain tests. These tests can be realized partly on the instillations built for this purpose (fords, test channels, etc.), where it is possible to verify the basic parameters of a vehicle movement ability (depth of wading, borderline between wading and swimming, influence of flow velocity on vehicle movement. The river bottom bearing capability can also be measured with a penetrometer.

Acknowledgments
This paper is a particular result of the defence research intentions DZRO K-210 NATURENVIR, DZRO K-202 MOBAUT and Specific research project 2017 at the department K-210 managed by the University of Defence in Brno and project of Masaryk University under the grant agreement No. MUNI/M/0846/2015, which is called ‘Influence of cartographic visualization methods on the success of solving practical and educational spatial tasks’.

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