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Application of DTW index in MIP model for fire ponds and access routes layout optimisation †

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Abstract: Wildfires are a significant worldwide problem. In Russia alone, they caused about 150 million euros worth of damage in 2020. Therefore the development of solutions to control forest fires is particularly important. In this paper, we have proposed a Depth-To-Water index-based solution to find the optimal location of fire ponds and access roads to them. We created digital Depth-To-Water maps in a geographic information system for two datasets: in Lohusuu, Estonia, and Podporozhye, Russia. Potential fire ponds were derived using a mixed-integer programming model with spatial Depth-To-Water data based on one fire pond of 100 m^3 per forest compartment. We generated access routes for firefighting vehicles to ponds using a mixed-integer programming model, taking into account the existing road network. The results obtained in combination with the known compartments' fire hazard classes allow both to reduce potential losses from wildfires and to ensure compliance with the requirements of existing Government regulations.

Keywords: wildfires; depth-to-water index; mixed integer programming; fire ponds; optimisation

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1. Introduction

Forest fires are a significant worldwide problem, causing significant environmental and financial damage. According to the Court of Auditors report [1], wildfires in Russia alone for five years caused more than 1 billion euros damage. An increase of anthropogenic impact on dendrocenoses and gradual climate warming entails losses of old-growth stands due to wildfires [2]. Therefore, the development of solutions to control forest fires is particularly important.

P. Bettinger, in the review [3], describes works from the 1970s through 2010 on incorporating wildfires into mathematical models of forest management. Rodríguez-Veiga et al. [4,5] developed mathematical models to allocate refuelling points for firefighting helicopters. The first is the multi-objective model, emphasising water download and integer linear programming model for allocation of resources in different periods during the planning period. Huang [6], Zhou [7], Chevailer [8], Tjurin [9] work on optimal placement of firefighting infrastructure in terms of optimal distances, time of arrival to the fire, or optimal use of resources. Sednev [10] proposes to arrange fire ponds in a chain with a pitch of 100 m with a slight overlap. Holusa et al. [11] developed a distance-based model developed for calculating optimal shuttle transport of water and the use of different types of water supply points for the Czech Republic.

In this paper, we propose to optimize the allocation of fire ponds for protection against wildfires by applying the DTW index. DTW is a soil moisture index based on the assumption that soils closer to surface water, in terms of distance and elevation, are more likely to be saturated [12,13]. The hypothesis is to apply the DTW index to better plan the layout of fire ponds and access roads to them. Different approaches can be used to solve the problem; in this paper, we propose creating a fire pond with the attraction to drier areas. Wildfires are more likely to break out on dry plots. Therefore, it is suggested to place a fire pond on the drier territory, which will serve as a drain or source of water for firefighting. To implement this approach, a coefficient based on the DTW index was included in the objective function.

The proposed approach was tested on two datasets (Podporozhye, Russia and Lohusuu, Estonia) with 625 and 150 km^2, respectively.

2. Materials and Methods

Within two areas of interest classified as forests [14–16], regular networks with a square side equal to 200-400 m were created. The centroid cells of the regular network were considered as potential locations of artificial fire ponds. The points were assigned a value of the construction cost of the artificial fire pond and the DTW index value. To optimize access roads layout, potential road network graphs were created. A description of the methodology for creating input data for mathematical models is included in the used datasets' descriptions.

2.1. MIP mathematical model for fire ponds' layout optimisation

The objective function (1) is to minimize costs, consisting of the cost of construction of fire ponds, the penalties for the distance of the built fire pond from the existing road network, minus the incentives for construction of fire ponds in areas with a higher value of the index DTW. Constraints (2) allow only one fire pond per block. Constraints (3) prohibit fire ponds that are less than the minimum allowable distance from each other.

Objective function:

$$\sum_{v,c} vFP_{v,c} \cdot pC_v + \sum_{v,c} vFP_{v,c} \cdot pRoadD_v \cdot pPdist - \sum_{v,c} vFP_{v,c} \cdot pIdtw_v \cdot pPdtw \rightarrow min \quad (1)$$

Table 1. Indices and sets

Set	Index	Description
sV	v, v_i, v_j	Graph vertices (fire ponds' potential locations)
sC	c	Compartments

Table 2. Parameters

Parameter	Description
pX_v	Coordinate X of the vertex v
pY_v	Coordinate Y of the vertex v
pC_v	The construction cost of the artificial fire pond in the vertex v, euro
pD_{v_i,v_j}	Distance from the vertex v_i to the vertex v_j, km
$pIdtw_v$	DTW index for the vertex v, m/m
$pPdtw$	DTW incentive, euro
$pMdist$	Min allowable distance between two fire ponds, km
$pFdist_{v\_i,v\_j}$	1, if distance from the vertex v_i to the vertex v_j less than $pMdist_{v\_i,v\_j}$ 0, otherwise
$pPdist$	Penalty for distance, euro/m
$pRoadD_v$	Distance from the vertex v to the closest existing road, km
$pM_{v,c}$	1, if vertex v is located in compartment c 0, otherwise

Table 3. Variables

Variable	Description
$vFP_{v,c}$	1, if fire pond is built in vertex v located in compartment c 0, otherwise

Table 4. Variables properties

Variable	Type	Lower bound	Upper bound	Index domain
$vFP_{v,c}$	binary	0	1	$pM_{v,c}=1$

Constraints:

$$\sum_{v} vFP_{v,c} = 1 \quad (2)$$

$$\sum_{c} vFP_{v\_i,c} + \sum_{v\_j|\ pFdist_{v\_i,v\_j}=1} \sum_{c} vFP_{v\_j,c} <= 1 \quad (3)$$

2.2. LP mathematical model for fire ponds access routes layout optimisation

The model's objective function (4) is to minimize access routes to fire ponds construction costs. The equation (5) is a transshipment constraint where for each vertex, the sum of incoming and outcoming flows is equal to 0. Herewith, to model accessibility and take into account the corresponding costs, the following parameters are used: 1 for the vertex representing the constructed fire pond, -1 for the graph exit vertex, 0 for all other vertices. As a result of the mathematical model II solution, the network of access routes to fire ponds was developed.

Model II computations were performed using the author's iterative heuristic algorithm based on the Anderson & Nelson algorithm [17]. The model found a minimum cost road network connecting one fire pond and graph exit vertex at each step of the algorithm. The graph edges for which $vFP_{v\_j,v\_i} = 1$ was true were equated to 1 euro/km cost construction, which was passed to the next step of the algorithm. The number of algorithm steps is equal to the number of planned fire ponds of the model I. The order in which the fire ponds were enumerated was according to the increasing distance from the fire ponds to the existing road network.

Objective function:

$$\sum_{v\_i,v\_j|pEA_{v\_i,v\_j}=1} vFP_{v\_i,v\_j} \cdot pLen_{v\_i,v\_j} \cdot pCC_{v\_i,v\_j} \rightarrow min \quad (4)$$

Table 5. Indices and sets

Set	Index	Description
sV	v, v_i, v_j	Graph vertices

Table 6. Indices and subsets

Subset	Index	Subset of	Description
ssP	p	sV	Graph vertices with fire ponds
ssQ	q	sV	Graph exit vertex

Table 7. Parameters

Parameter	Description
pCC_{v_i,v_j}	The construction cost of the edge from the vertex v_i to the vertex v_j, euro/km
$pLen_{v\_i,v\_j}$	Length of the edge from the vertex v_i to the vertex v_j, km
pEA_{v_i,v_j}	1, if the edge from the vertex v_i to the vertex v_j is a part of the feasible region 0, otherwise
pEN_v	1, if the vertex v is a part of the feasible region 0, otherwise
pFB_v	1 | $v \in ssP$ 0 | $v \in sV$ and $v \notin ssP$ and $v \notin ssQ$ -1 | $v \in ssQ$

Table 8. Variables

Variable	Description
vFP_{v_i,v_j}	1, if the edge from the vertex v_i to the vertex v_j is a part of the solution 0, otherwise

Table 9. Variables properties

Variable	Type	Lower bound	Upper bound	Index domain
vFP_{v_i,v_j}	continuous	0	1	pCC_{v_i,v_j}> 0 and pEA_{v_i,v_j}=1

Constraints:

$$\sum_{v_j} vFP_{v_j,v_i} + pFB_{v_i} = \sum_{v_j} vFP_{v_i,v_j} \tag{5}$$

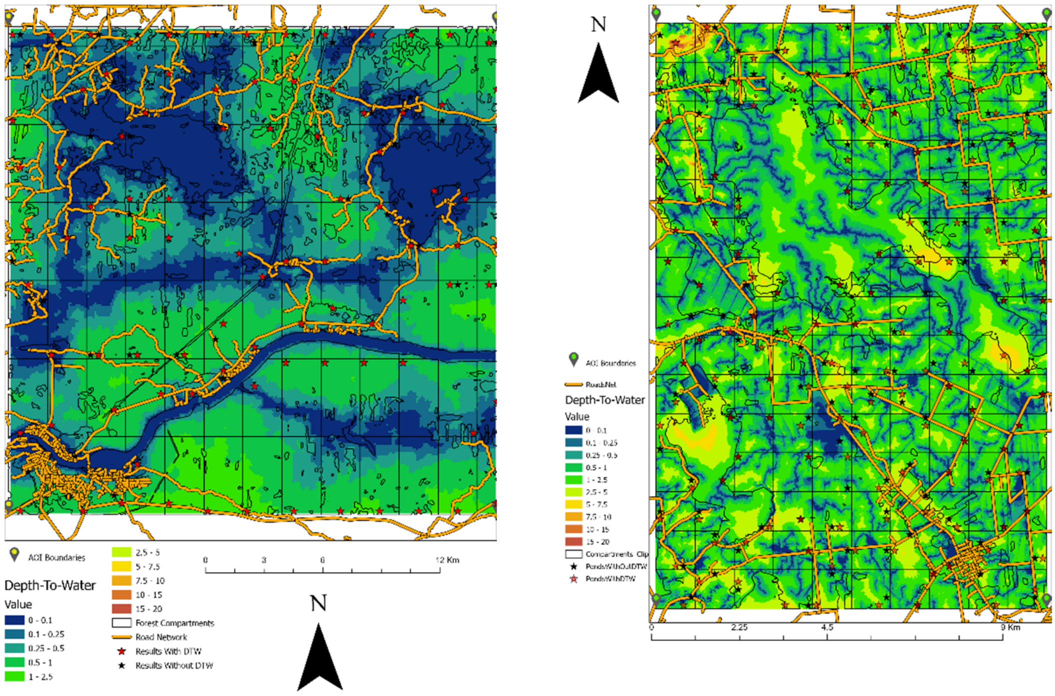
The calculations for each of the two models were performed on a MSI GT72VR 7RE laptop using the AIMMS Community Edition License with solver CBC 2.9.

3. Results

DTW maps were obtained for each dataset, as well as optimal fire ponds allocation, and road network layout (Figure 1).

The solution of the model I resulted in a list of vertices where fire ponds are proposed to be built. The problem was solved twice: with and without DTW index.

As a result of the model II, the resulting graph of the road network was obtained, including the existing road network and the edges chosen for the construction of fire ponds access roads.



(**a**) (**b**)

Figure 1. Planned fire ponds: (**a**) Podporozhye, Russia; (**b**) Lohusuu, Estonia.

4. Discussion

The practical application of the developed methodology is to overlay the DTW-map on a known map of fire hazard areas; for example [18], it is possible to obtain both potential locations for fire ponds and those forest areas where fire ponds are not required.

Ways to further improve the model are:

- Layout planning of more than one fire pond per compartment, taking into account the normative area of stands provided with fire ponds, and the minimum distance between fire ponds, depending on the fire hazard class of the compartment;
- Creation of a fire pond with an attraction to wetter areas;
- Layout planning of access roads to existing natural water sources for their use as fire ponds.

5. Conclusions

The developed solution provides potential locations for the fire ponds and access roads to them, taking into account the index DTW.

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References

1. Court of Auditors report Available online: https://ach.gov.ru/upload/iblock/247/247d140a4eb4b0607c43b585a2a5e0ee.pdf (accessed on Jun 21, 2021).
2. Hansen, M.C.; Potapov, P. V.; Moore, R.; Hancher, M.; Turubanova, S.A.; Tyukavina, A.; Thau, D.; Stehman, S. V.; Goetz, S.J.; Loveland, T.R.; et al. High-Resolution Global Maps of 21st-Century Forest Cover Change. *Science (80-.).* **2013**, *342*, 850–853, doi:10.1126/science.1244693.
3. Bettinger, P. An overview of methods for incorporating wildfires into forest planning models. In Proceedings of the Mathematical and Computational Forestry and Natural-Resource Sciences; 2010.
4. Rodríguez-Veiga, J.; Gómez-Costa, I.; Ginzo-Villamayor, M.J.; Casas-Méndez, B.; Sáiz-Díaz, J.L. Assignment problems in wildfire suppression: Models for optimization of aerial resource logistics. *For. Sci.* **2018**, doi:10.1093/forsci/fxy012.
5. Rodríguez-Veiga, J.; Ginzo-Villamayor, M.J.; Casas-Méndez, B. An integer linear programming model to select and temporally allocate resources for fighting forest fires. *Forests* **2018**, doi:10.3390/f9100583.
6. Huang, Y.; Fan, Y.; Cheu, R.L. Optimal allocation of multiple emergency service resources for protection of critical transportation infrastructure. *Transp. Res. Rec.* **2007**, doi:10.3141/2022-01.
7. Zhou, S.; Erdogan, A. A spatial optimization model for resource allocation for wildfire suppression and resident evacuation. *Comput. Ind. Eng.* **2019**, doi:10.1016/j.cie.2019.106101.
8. Chevalier, P.; Thomas, I.; Geraets, D.; Goetghebeur, E.; Janssens, O.; Peeters, D.; Plastria, F. Locating fire stations: An integrated approach for Belgium. *Socioecon. Plann. Sci.* **2012**, doi:10.1016/j.seps.2012.02.003.
9. Tjurin, N.A.; Gromskaya, L.Y.; Antonova, T.S.; Zubova, O.V.; Siletskiy, V.V.; [Тюрин, Н.А.. Optimization location of forest fire stations. *Izv. Sankt-Peterburgskoj Lesoteh. Akad. [Известия Санкт-Петербургской лесотехнической академии]* **2019**, 224–235, doi:10.21266/2079-4304.2019.227.224-235.
10. Sednev, V.A.; Lopuhova, N.V. The Method of Determining the Amount and Substantiation of the Layout of Fire Water Reservoirs in Rural Village. *Vestn. Saint Petersbg. Univ. State Fire Serv. EMERCOM Russ.* **2018**, 37–41.
11. Holuša, J.; Koreň, M.; Berčák, R.; Resnerová, K.; Trombik, J.; Vaněk, J.; Szczygieł, R.; Chromek, I. A simple model indicates that there are sufficient water supply points for fighting forest fires in the Czech Republic. *Int. J. Wildl. Fire* **2021**, *30*, 428, doi:10.1071/WF20103.
12. Murphy, P.N.C.; Ogilvie, J.; Connor, K.; Arp, P.A. Mapping wetlands: A comparison of two different approaches for New Brunswick, Canada. *Wetlands* **2007**, doi:10.1672/0277-5212(2007)27[846:MWACOT]2.0.CO;2.
13. White, B.; Ogilvie, J.; Campbell, D.M.H.; Hiltz, D.; Gauthier, B.; Chisholm, H.K.; Wen, H.K.; Murphy, P.N.C.; Arp, P.A. Using the cartographic depth-to-water index to locate small streams and associated wet areas across landscapes. *Can. Water Resour. J.* **2012**, doi:10.4296/cwrj2011-909.
14. Elevation Data Geoportal Available online: https://geoportaal.maaamet.ee/eng/Spatial-Data/Elevation-data-p308.html (accessed on May 6, 2021).
15. Simonenkova, A.; Simonenkov, M.; Bacherikov, I. Dataset: Podporozhye Available online: https://data.mendeley.com/datasets/39b9bbprcx/1.
16. Simonenkova, A.; Simonenkov, M.; Simonenkov, E.; Bacherikov, I. Dataset: Estonia Available online: https://data.mendeley.com/datasets/svp3xmmt23.
17. Anderson, A.E.; Nelson, J. Projecting vector-based road networks with a shortest path algorithm. *Can. J. For. Res.* **2004**, *34*, 1444–1457, doi:10.1139/X04-030.
18. European Forest Fire Information System Available online: https://effis.jrc.ec.europa.eu/ (accessed on Jun 21, 2021).