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D8 flow model for pollutants dispersion: A case study at Bogdalen watershed between the Raudfjell and Kvitfjell wind farm, North of Norway

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Abstract. Investments in wind power are booming in Norway. Several wind power plants have been constructed to exploit the wind energy. However, construction of wind farms has potential impacts on the surrounding environment. Particularly, waste from construction site or activities of workers, leakage of oil and chemical would spread into the nearby waterbodies by runoff or infiltrating into ground. Hence, quality of surface water and ground water would be degraded. Raudfjell and Kvitfjell is the biggest on-shore wind power project in the north of Norway and is underconstruction. However, water quality around these two wind farms has been reported to be seriously polluted. The pollutants in the water are expected to disperse to surrounding area by runoff and accumulate at certain accumulation areas in the watershed. Therefore, it is of great importance to identify the directions of pollutants transportation and the potential vulnerable areas that may be affected by the pollution. This paper built up a D8 flow model to investigate pollutants dispersion at the small-scale watershed Bogdalen located between Raudfjell and Kvitfjell wind farm area. The model identified in detail possible single-flow directions on each cell of ground surface and detected the potential pathways where pollutants are expected to transport to and accumulate. The results stated that the model has provided promising results for pollution management.

1. Introduction

Raudfjell and Kvitfjell (figure 1) constitute the biggest on-shore wind power project in the north of Norway. This project will contribute significantly to meet the target of new renewable power for the electricity market of Norway and Sweden. In addition, these wind farms support positive benefits for security of supply in the region [1]. The two wind farms cover an area of 2,505 ha, of which Kvitfjell has 1,380 ha and Raudfjell has 1,125 ha. It is planned totally 67 wind turbines with maximum capacity of 300 MW (200 MW from Kvitfjell and 100 MW from Raudfjell). The annual electricity production of 1,020 GWh would be generated from the two wind farms, of which 680 GWh is from Kvitfjell and 340 GWh is from Raudfjell [2]. The electricity could support enough annual power for around 50,000 households [3].

The perspective benefits of Raudfjell and Kvitfjell wind farm is clearly defined. However, the construction and operation of the wind farm afterwards would have potential negative impact on the surrounding environment. For instance, serious pollution of water quality in the watersheds near the wind farm has been reported. The contaminants in the water is expected to spread into surrounding

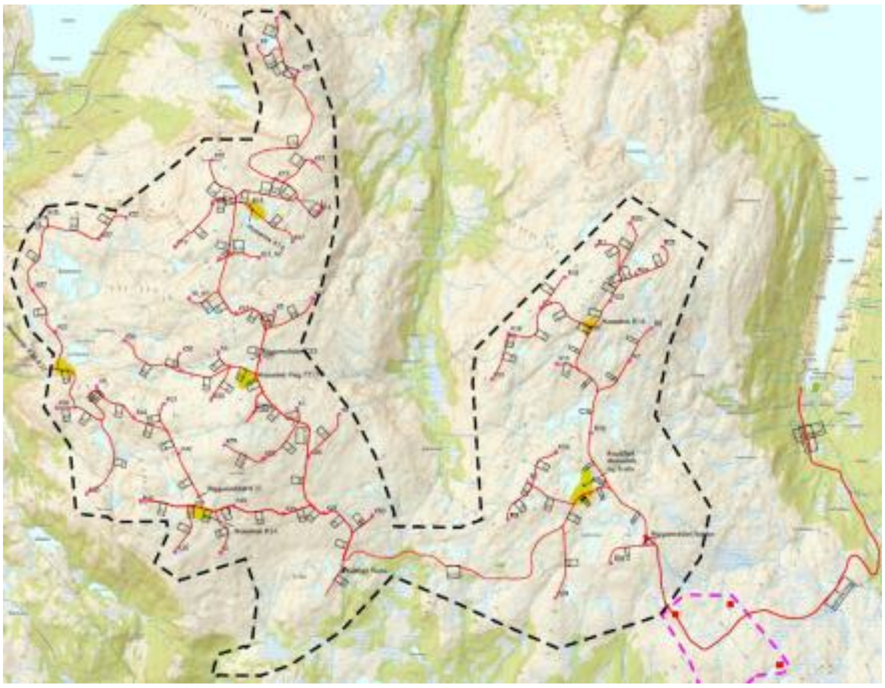

Figure 1. Location of Raudfjell and Kvitfjell wind farms and distribution of wind turbines (source: [4]).

environment by runoff from rainfall. The area in between these two wind farms is Bogdalen watershed, which has topography of a valley. Hence, this area could be impacted significantly by the pollution from the wind farms since pollutants tend to transport from the high elevation and accumulate in flat area. Water samples at near outlet of Bogdalen are polluted by clostridium perfringens, presumptive E.coli, intestinal enterococci, coliform bacteria [5]. Especially, at two locations in the upperparts of the watershed, water has high concentration of Mn and Al, whose concentration exceeds the threshold limit for drinking water [5]. If these contaminants are spreaded further downstreams by rainwater, the vulnerable affected area is definitely widened. Therefore, it is of great importance to determine where pollutants are from and where it could be dispersed. This paper will develop a D8 flow model to identify directions of pollutants dispersion based on single-flow analysis of surface runoff and use the model for the whole Bogdalen watershed. The aim is to identify the source of the pollution for each single point within the watershed and the vulnerable areas that can be affected by the pollution from the watershed.

2. Study area

Bogdalen watershed is located between Raudfjell and Kvitfjell wind farm. The watershed covers an area of 12.86 km^2. The average and maximum elevation of this area, which is statistically analyzed from DEM, is 325 m and 560 m perspectively (figure 2(a)).

According to long-term data from Norwegian Water Resources and Energy Directorate, the annual air temperature fluctuates from 2-4^{o}C, for 1971-2000 period (figure 2(b)). The annual precipitation of Bogdalen watershed varies from 1,500-2,000 mm, for 1971-2000 period (figure 2(c)), and annual runoff distributes in a range of 600-1,500 mm, for a 30-year period from 1961-1990 (figure 2(d)).

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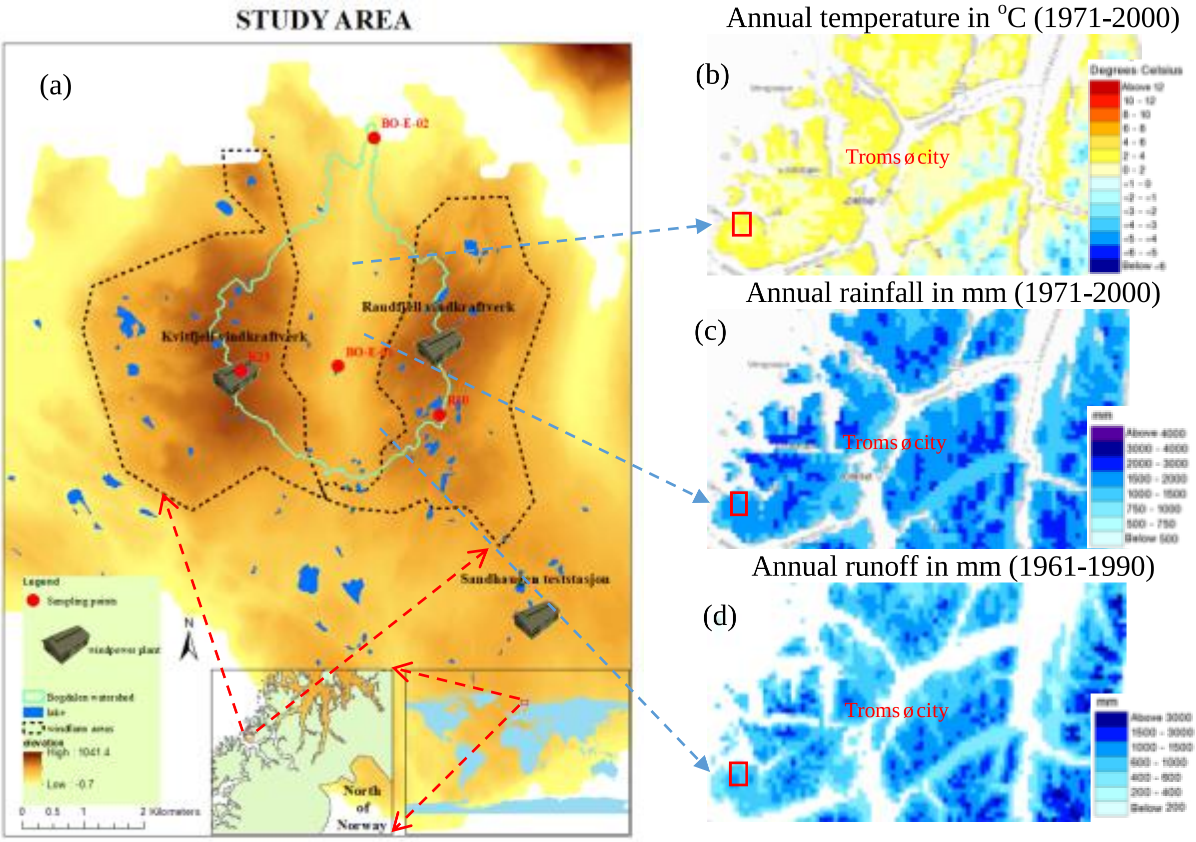


Figure 2. (a) location of Bogdalen watershed; (b) annual temperature; (c) annual rainfall; (d) annual runoff (source: [2]).

3. Material and methodologies

3.1. Data collection

3.1.1. Digital elevation map (DEM). Digital Elevation Map (DEM) with 10x10 m resolution was collected from the Norwegian Mapping Authority-Geonorge, the national website for map data and other location information in Norway. DEM collection and processing is described in detail in figure 3: from the grid cell of DEM for the whole Norway (1), pick up a grid cell that includes the study area (in blue rectangular, code 7706_3) and download to computer (2), using ArcGIS version 10.5 to clip DEM data for study area, Bogdalen watershed (3).

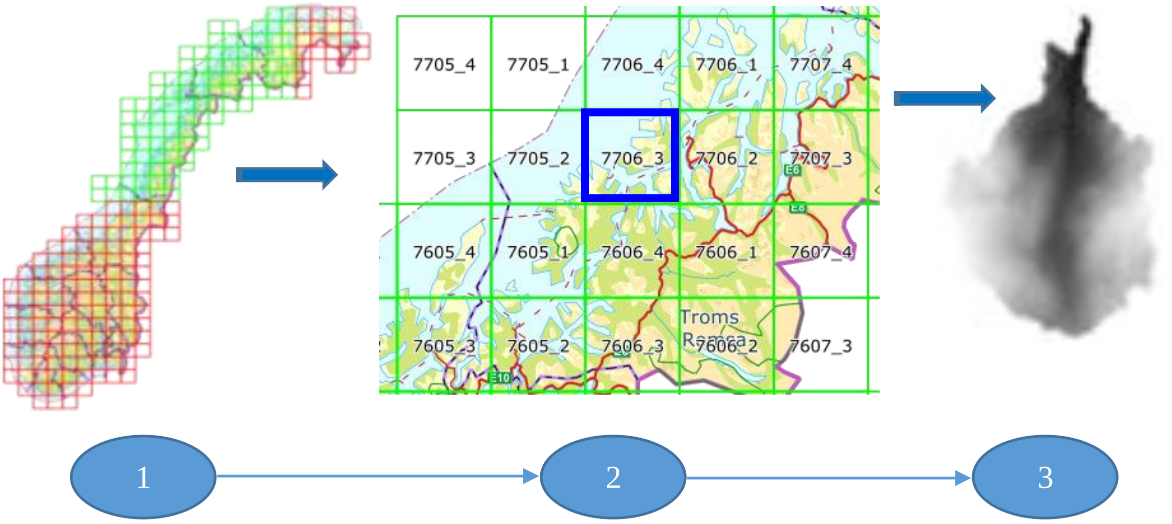


Figure 3. DEM collection.

3.1.2. Other vector data. Other vector data such as river network, lake, watershed boundary, administration boundary, wind farm area, wind power plant are collected from the Norwegian Water Resources and Energy Directorate – NVE for mapping purposes.

3.2. D8 flow model

A D8 flow model was applied in this study to investigate pollutants dispersion based on single-flow direction analysis. This model has been successfully used in several case studies to study acid mine drainage pollution problem [6-9]. This model was also applied previously in drainage control for water pollution [10,11].

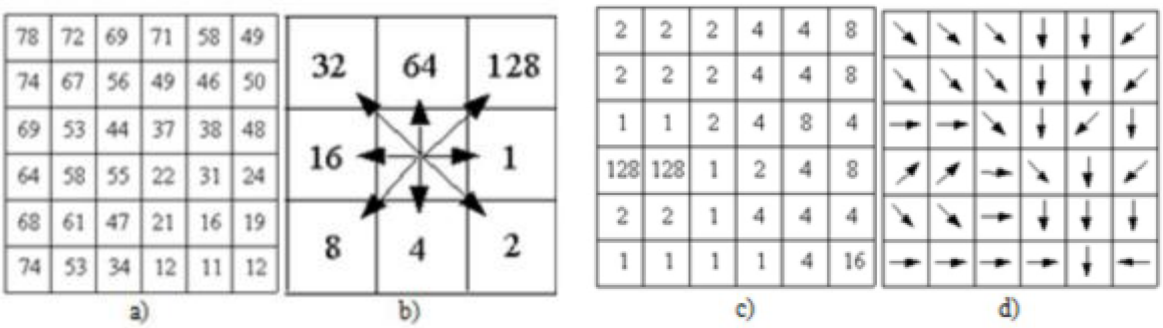


Figure 4. Flow direction analysis by D8 flow model, a) Elevation of each cell from DEM, b) Matrix 3x3 of flow direction code, c) Grid code outputs, d) Arrow symbols of flow direction for each cell, modified from [12].

D8 flow model is a kind of deterministic model for stream direction. It is quite important in hydrological model to point out the direction where water will flow on the ground surface [12-16]. The model needs Digital Elevation Map-DEM as the main input. The concept of D8 flow model is to find on each grid cell of DEM (figure 4(a)) the direction where water will travel. There are totally eight output directions where water could flow corresponding to eight adjacent cells, which is called as a matrix 3x3 with code for each direction (figure 4(b)). The code in the matrix increases from the smallest of 1 to the highest of 128. Code 1, 2, 4, 8, 16, 32, 64 and 128 is at eastern direction, the southeastern direction, the south direction, the southwestern direction, the west direction, the northwestern direction, the north and the northeast direction respectively. In addition, directions of flow indicated by code numbers rotate clockwise. The model will detect which adjacent cell has the steepest drop, and water will then flow into that direction. The steepest drop is calculated by the following equation:

$$\text{Steepest drop} = \text{change in z value} / \text{distance} * 100$$

where: z is elevation of each cell in DEM; distance is calculated between cell centers.

After the direction of the steepest drop is detected, the output cells are given codes with the number regarding the direction of flow (figure 4(c)). Finally, direction of flow on each cell of the topography map was visualized by arrow symbols (figure 4(d)).

D8 flow model was built in ArcGIS version 10.5 by ModelBuilder toolbox. The whole process was illustrated in figure 5. Firstly, model needs DEM as input in blue oval shape. Afterwards, a “Fill” tool from hydrological toolbox is used to fix the error of surface topography (in orange rectangular shape), The output of filled DEM is indicated in the next green oval shape of the process. The next step is to identify flow direction by “Flow Direction” tool in orange rectangular shape. Finally, output drop raster (in white oval shape) and output flow direction raster (in green oval shape) are generated.

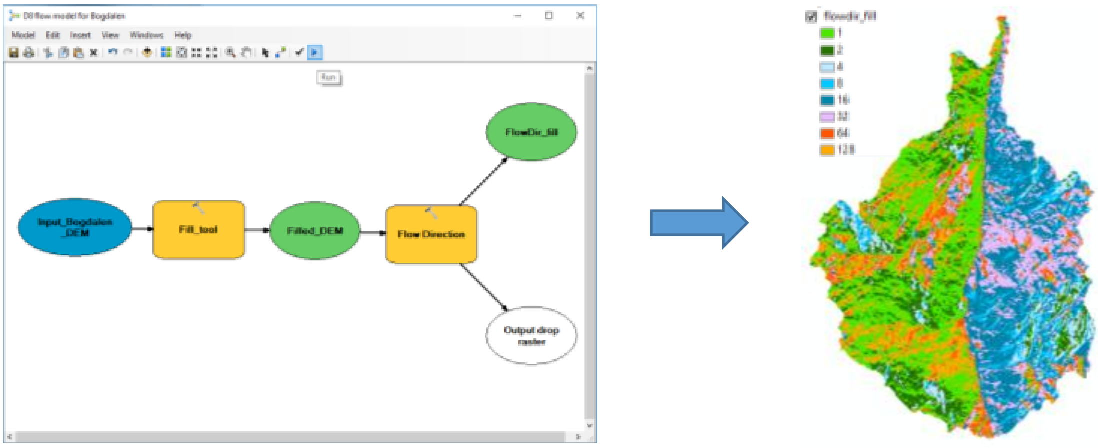


Figure 5. ModelBuilder for a D8 flow model in ArcGIS.

4. Results and discussion

Flow directions are analysed for the whole Bogdalen watershed and are displayed in figure 6. The eight flow directions are coded with different colors: east (E) in green, southeast (SE) in dark green, south (S) in light blue, southwest (SW) in blue, west (W) in dark blue, northwest (NW) in light pink, north (N) in red, and northeast (NE) in orange. Hence, no matter which pollutant point within the watershed, pathways of pollution transportation by rainwater can be estimated based on flow directions. Four sampling points are set up for this watershed namely K23, K10, BO-E-01 and BO-E-02. Chemical analysis of water samples at K23 and K10 [5] indicated high concentration of Al and Mn, which are higher than drinking water standards by Ireland Environmental Protection Agency [17]. Hence, elaborate analysis of flow direction around K23 and K10 sampling points are carried out to investigate the potential pathways where pollution could be transported and accumulated.

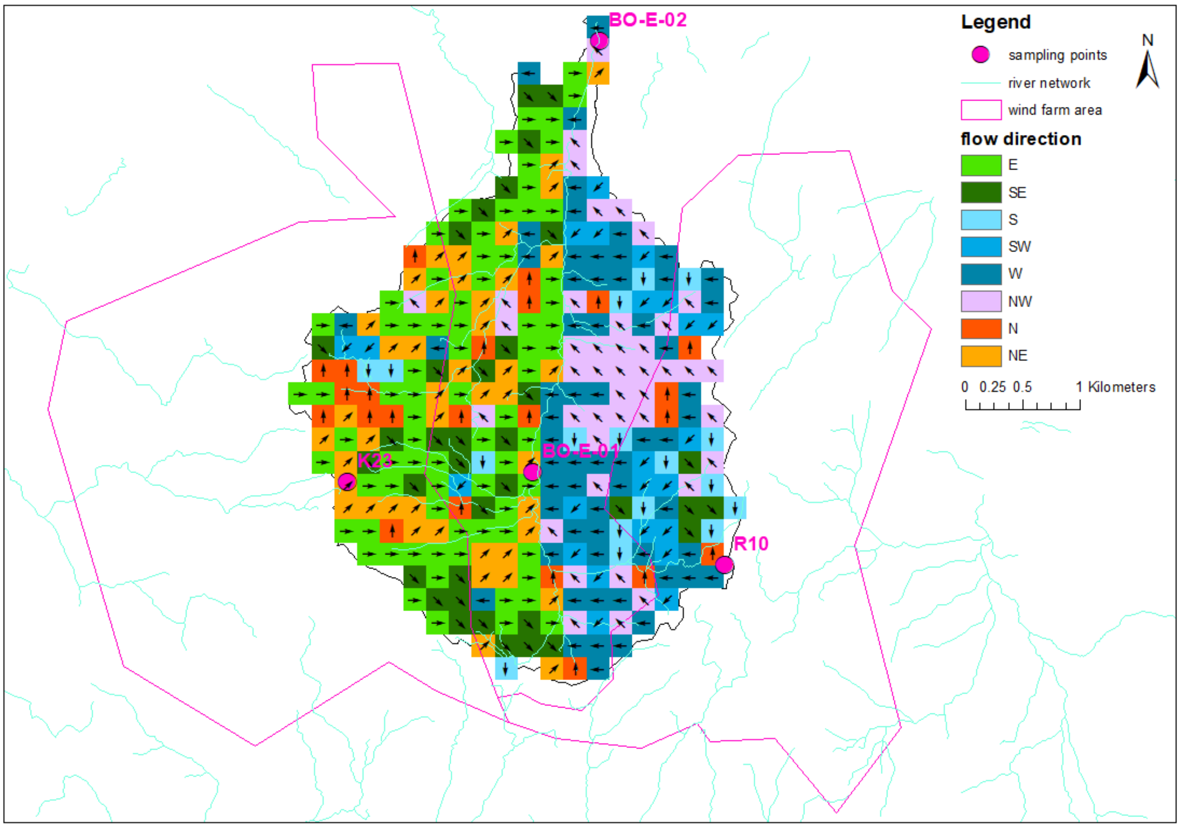
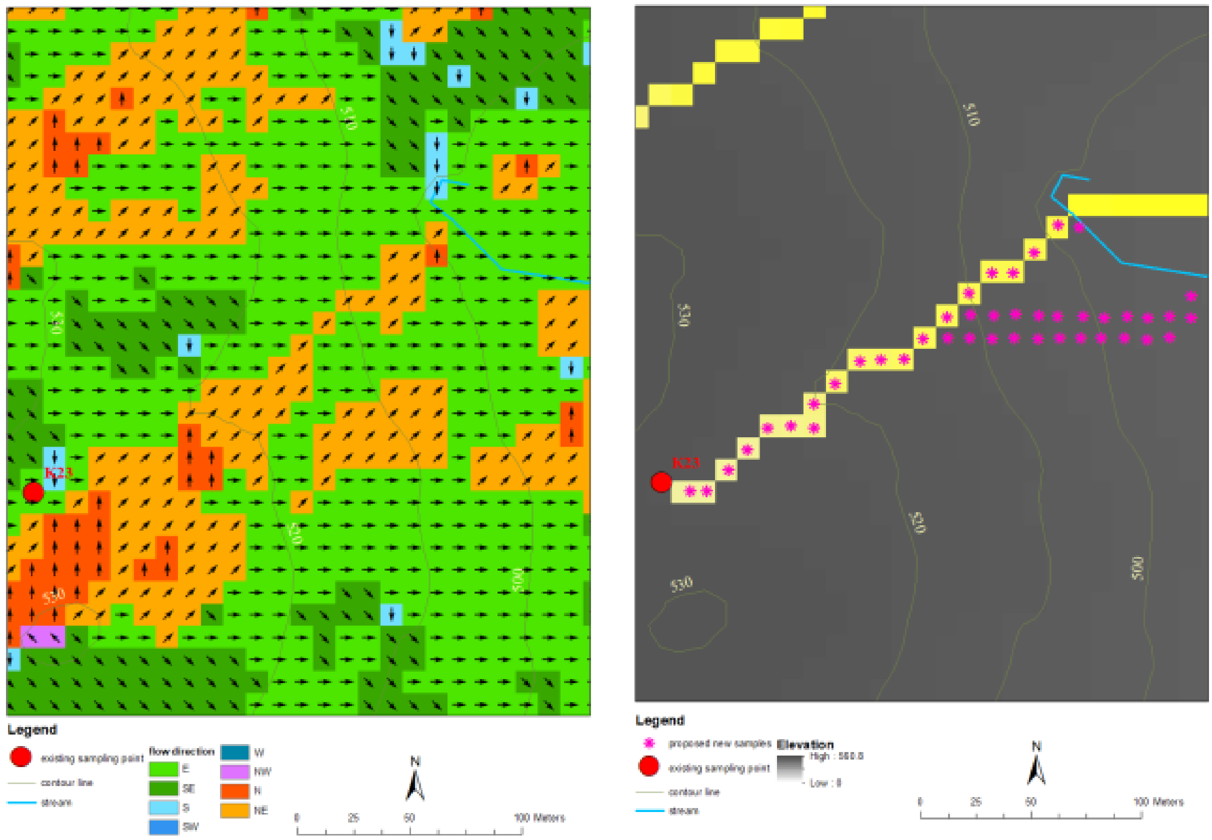


Figure 6. Flow direction analysis for the whole Bogdalen watershed.

4.1. Flow direction analysis at sampling point K23

Sampling point K23 is inside Kvitfjell wind farm. D8 flow model detects elaborately single flow direction around sampling point K23 as in figure 7(a). K23 is located in the area with eastern flow direction (green colors), however, after that the flow direction will move to the northeast (orange colors). A pathway of flow accumulation (yellow grid cells) is detected based on the aggregate of several single-flow directions (figure 7(b)). The pollutants are expected to travel and accumulate along this route. Therefore, more samples should be collected on this pathway to detect variation of pollutant concentration. In case high runoff as a result of heavy rainfall, pollutant would move out the accumulation pathway and spread into east direction (green color cells) because of overflow from the accumulation flow pathway, and the area in eastern direction would be impacted. Hence, more samples are suggested to collect in this area as well for further investigation of pollution. Figure 7(b) suggests that more samples (in pink colors asterisks) should be collected to verify where and how far the pollutant will transport from the pollution point.

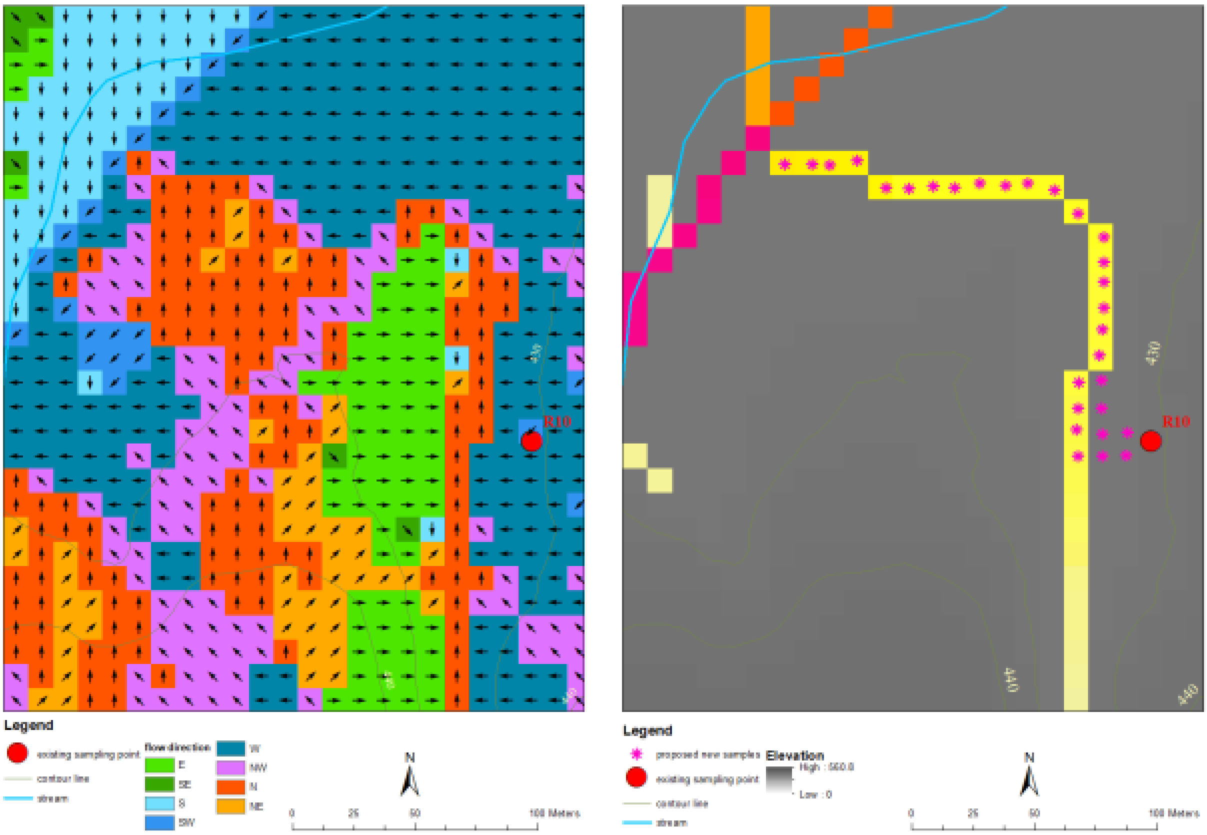


(a) (b)

Figure 7. (a) single-fow direction around sampling point K23 and (b) proposed new sampling points based on flow direction and flow accumulation pathways.

4.2. Flow direction analysis at sampling point K10

K10 sampling point belongs to Raudfjell wind farm. Surface runoff passes through sampling point K23 in western direction (area with dark blue colors, figure 8(a)). The water then travels to the north where there is a route of flow accumulation (in red color cells, figure 8(a)), then turn back to the west direction. An accumulation pathway is detected for this area as in figure 8(b) with yellow cells. More samples (pink colors asterisks) are proposed to collect for testing pollution transportation (figure 8(b)).



(a) (b)

Figure 8. (a) single-fow direction around sampling point K23 and (b) proposed new sampling points based on flow direction and flow accumulation pathways.

4.3. Reliability of the results

Result of D8 flow model depends much on high resolution of DEM and the accuracy of sampling points' coordination. Error from interpolation process of ground surface elevation, therefore, could result in uncertainty of the model. Also, if location of sampling points is not really correct, then the interpretation of pollutant transport pathways will give the unexpected results. Moreover, number of samples at each sampling point is still too low; hence, it is recommended that more samples should be collected in future for better understanding of pollutants dispersion as well as for model validation.

5. Conclusion

A D8 flow model was built in this study to investigate pollutants dispersion at the small-scale watershed Bogdalen in northern Norway that crosses both the Raudfjell and Kvitfjell wind farm. The model already detected the flow directions for the whole study area, particularly focus in detail on two sampling points where the pollution of Al and Mn is indicated by sample analysis. Pollutants are expected to transport following the direction of single flows. Results from the model could provide additional information of collecting samples for further pollution assessment. Hence, this would help to save time and cost of sampling compared to random collection approach.

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