PREDICTING STEADY STATE CONCENTRATIONS OF CHLORIDE IN GROUNDWATER AND SURFACE WATER.

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Abstract

A road in operation with its traffic can pose a serious pollutant threat to groundwater and surface water in its vicinity. Examples of pollutants are salt for deicing and dustbinding; metals from corrosion of vehicles and wear of road surface and tires; hydrocarbons from the wear of road surface, tires, exhaust, oils; and hazardous goods discharged in the case of an accident. In Sweden about 300000 tonnes of sodium chloride are used annually by the Swedish National Road Administration for deicing purposes. In addition the local municipalities also use salt for deicing purposes. The use of studs improve the friction but increase the wear and the grinding effect on winter roads. The wear of a wet surface is reported to be two to seven times the wear of a dry surface, and hence, the grinding effect may be further increased by the use of deicing salt.

The movement of pollutants from the road to the surrounding environment will involve run-off from roads, airborne spreading, infiltration from road construction and road area. The chloride ion is a good tracer. It is conservative and highly soluble and not subjected to retardation or degradation. A small part of the sodium may be retained in soil but almost all of the deicing salt will be either infiltrated and found in groundwater or form runoff and be found in surface water. Other, non-degradable road-related substances may be retained in soil to a greater extent. Eventually, all pollutants from roads, which are not subjected to degradation, will be transported either to surface water or to groundwater.

In this paper a method is presented by which the steady state concentration of chloride in groundwater and surface water due to the use of deicing salts can be calculated. The calculations are based on digital data for catchment areas, net recharge (precipitation with the deduction of evapotranspiration), background deposition and road network with deicing salt application rates. All data are processed and presented with the GIS-tool Arcview. The method makes its possible to scan an area, e.g. a country, in order to make the decisions on what areas to protect and which measures to adopt. The method can also be used to predict the steady state concentrations of other road related pollutants.

Introduction

A road in operation with its traffic can pose a serious pollutant threat to groundwater and surface water its vicinity. Examples of pollutants are salt for deicing and dustbinding; metals from corrosion of vehicles and wear of road surface and tires; hydrocarbons from the wear of road surface, tires, exhaust, oils; and hazardous goods discharged in the case of an accident. In Sweden about 300000 tonnes of sodium chloride are used annually by the Swedish National Road Administration for deicing purposes of national roads (Thunqvist 2000). In addition the local municipalities also use salt for deicing purposes.

The major roads in Sweden are deiced with 10-20 tonnes of sodium chloride per kilometre annually. On the road the effects of the salt are desired, and in the ocean a high salt concentration is

natural. However, on their way the sodium and the chloride ions will pass through an environment where the natural concentration of salt is low, involving an impact on the environment (Figure 1).
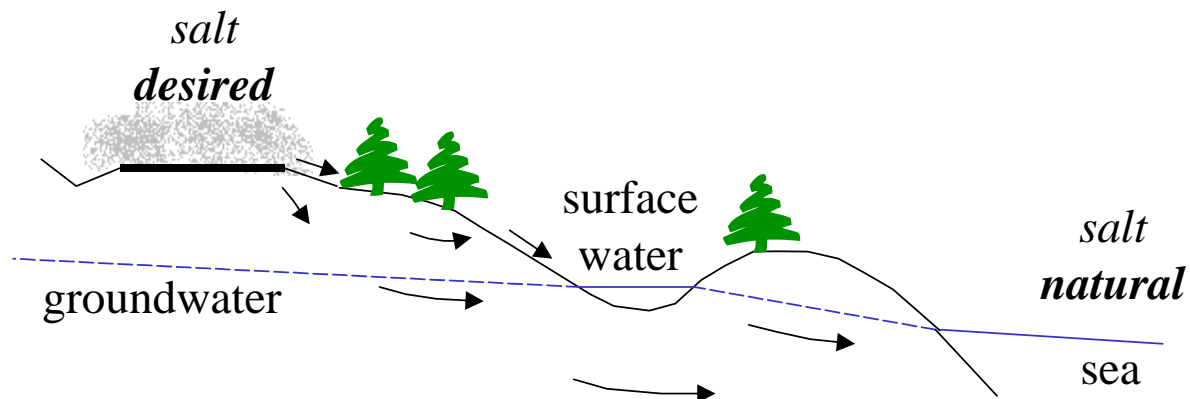

Figure 1. The movement of deicing salt from road to sea.

The chloride ion is a good tracer. It is conservative and highly soluble and not subjected to retardation or degradation. A small part of the sodium may temporarily be retained in soil but almost all of the deicing salt will by infiltration or runoff reach groundwater and surface water. Several Swedish investigations show that the chloride concentrations in both groundwater and surface water have increased in the vicinity of roads (e.g. Bäckman & Folkeson 1995, Olofsson & Sandström 1998, Thunqvist 2000). The movement of pollutants from the road to the surrounding environment will involve run-off from roads, splash, airborne spreading and infiltration from road construction and road area. Other, non-degradable road related substances may be retained in soil to a greater extent, but they will eventually reach groundwater or surface water. There are also several investigations which show that heavy deicing salt application increases metal mobilisation (Amrhein et al 1994, Bauske & Goetz 1993, Norrström & Jacks 1998).

The Swedish Environmental Code (SFS 1998:808, ch.2) states that everyone is required to possess the knowledge of the impact of one's activities and to implement protective measures in order to prevent impact on the human health and the environment. A simple and robust model to estimate the concentration of chloride in recharge water based on different salt application rates would be a first step towards that knowledge. It is of importance that the data are easily accessible and the processing tool well known.

This paper shows how such a simple model can be used to predict chloride concentrations in water due to application of deicing salt. If it is possible to scan an area, e.g. a county, it is possible to make the decisions on what areas to protect and which measures to adopt. The limitations of the model and how the results can be refined by the use of more indata or by the use of a more sofisticated model is discussed.

Background

There are different ways of combining the data which give different precision in identifying water in the vicinity of roads where there is a risk for high chloride concentrations. The simplest way is to combine the maps of the road network with maps of the hydrogeological conditions and maps of lakes and watercourses in order to identify risk areas. The result is a rough indication of where conflicts of interest exist between roads and groundwater/surface water. This method has been used by the Swedish National Road Administration in order to identify where the consequence of a road accident would be serious for a water supply (Vägverket 1995). However, the investigation has been limited to national roads and to municipal water supplies of a certain capacity. The actual number of important aquifers and lakes/watercourses in conflict with deiced roads is much greater. Furthermore, only the different sites of conflicting interest are listed - the increase in chloride concentration for different areas is not calculated. In Figure 2 the digital maps of the main roads are combined with digital maps showing the main aquifers in the county of Västmanland. Historically roads in Sweden were built on

good soil material high in the landscape. Thus, the roads are often built on the major eskers (which are also important aquifers) since they provided the necessary requirements.

The winter road maintenance categories are A1 to A4, B1 and B2. The A-roads are deicied regularly, where category A1 is the largest road with the most frequent recurring deicing operations. The B1-roads are deiced occasionally, although sand with a small amount of deicing salt added is used more frequently, and on the B2-roads even less deicing salt is used.
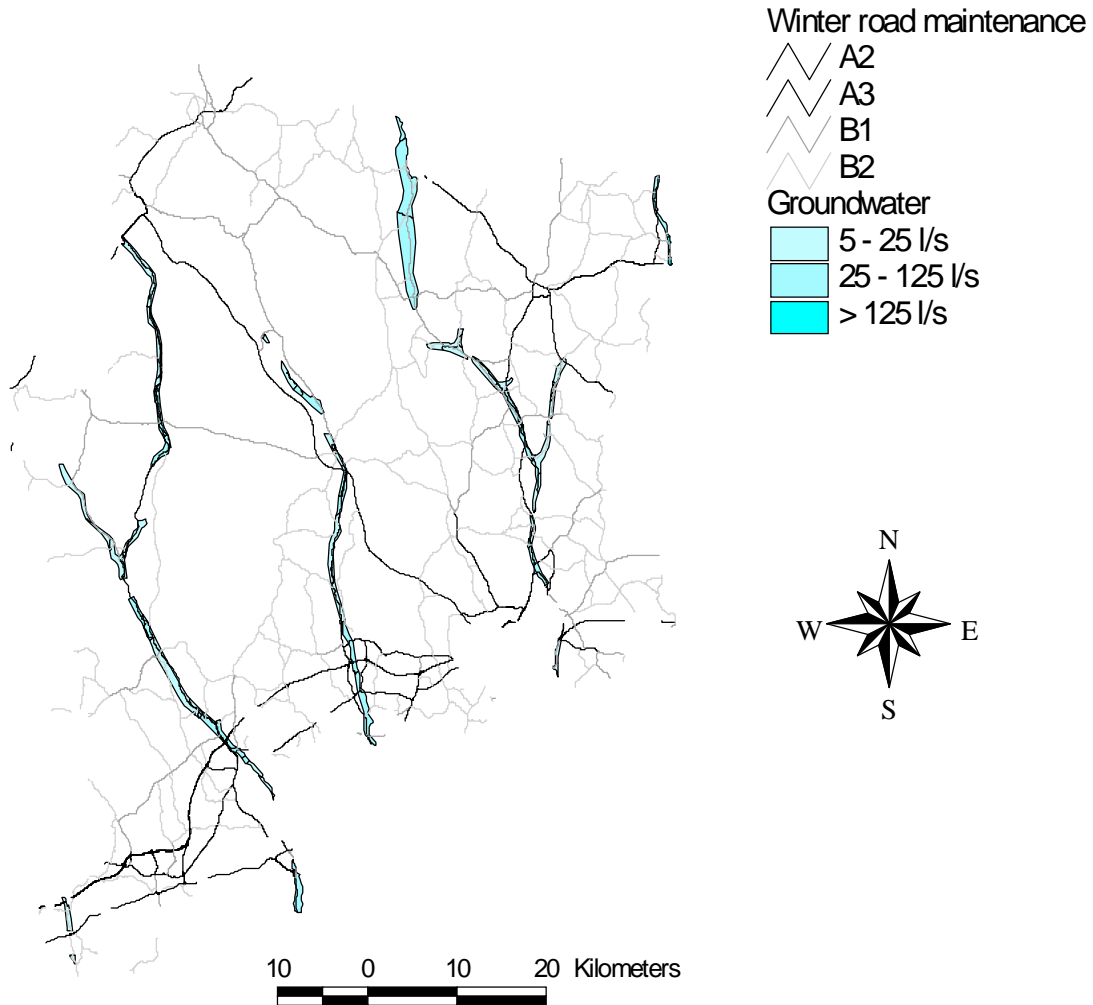
Figure 2. Intersections between major roads and major aquifers in Västmanland, Sweden.

A more general method is to apply the annual amount of deicing salt within the area and the annual net recharge to the catchment areas within the investigated area (Huling & Holocher 1972, Howard & Haynes 1993, Thunqvist 2000). In Sweden the National Swedish Meteorological and Hydrological Institute has estimated the catchment areas for the whole of Sweden and they are available in digital form. If it is assumed that deicing salt application has occurred sufficient time for steady-state conditions to be established, the average chloride concentration in the discharge will be the same as in the net recharge. During the first years of deicing salt application the chloride concentration in the recharge will be much higher than in the discharge. Hence, chloride will

accumulate in the storage and the concentration will increase. On conditions that the salt application is invariable the chloride concentration in discharge will eventually be the same as in recharge (steady state). The increase in concentration as a function of time is an exponential curve (Figure 3). The calculated chloride concentration from road salt is then added to the natural background deposition for the area.
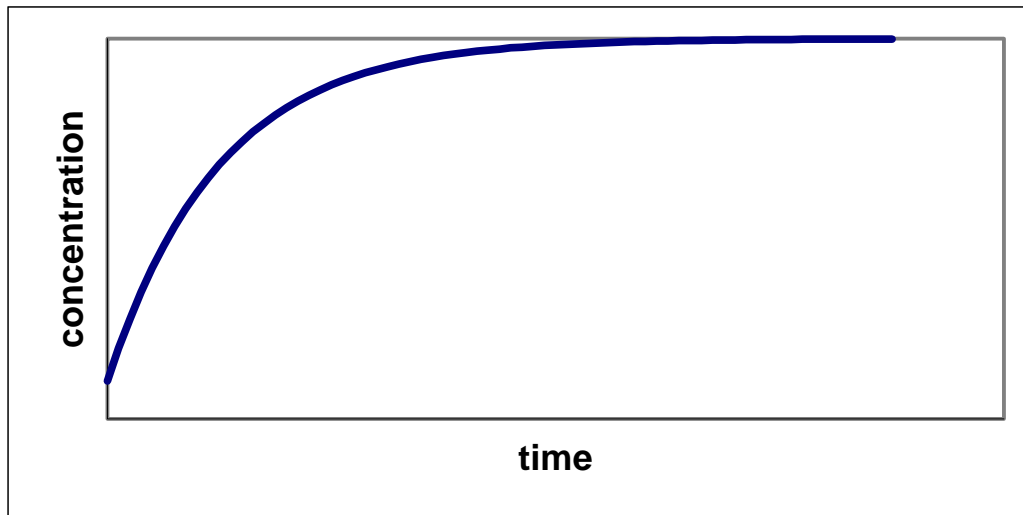

Figure 3. The exponential function for a complete-mix box model.

Methods and Materials

The average concentration in net recharge can be calculated as the annual average amount of chloride applied divided by annual net recharge for the area plus the natural background deposition.

$$[Cl]_{tot} = \frac{\dfrac{M_{Cl}}{M_{NaCl}} * m_{salt}}{(P-E)A} + [Cl]_{dep}$$

In order to make these calculations for a region the necessary digital data are:

- Maps showing the catchment area obtained from the Swedish Meteorological and Hydrological Institute (SMHI) or digital elevation data from which the catchment areas are obtained by the use of a Geographical Information System e.g. Arcview.

- Net recharge obtained from maps made by the Swedish Meteorological and Hydrological Institute.

- Natural deposition of chloride (considering the difference in deposition for different land use) in the area from the Swedish Environmental Protection Agency (SEPA 2000).

- National road network, the different road categories and the average amount of deicing salt applied for each category obtained from the National Swedish Road Administration.

All data are processed and presented with the GIS-tool Arcview.

Information on net recharge from SMHI is based on the annual average for the period 1961-1990. The natural background deposition values are calculated from deposition values 1985-1989 (SEPA 2000). Deicing salt application is based on annual average values for the period 1995-1999.
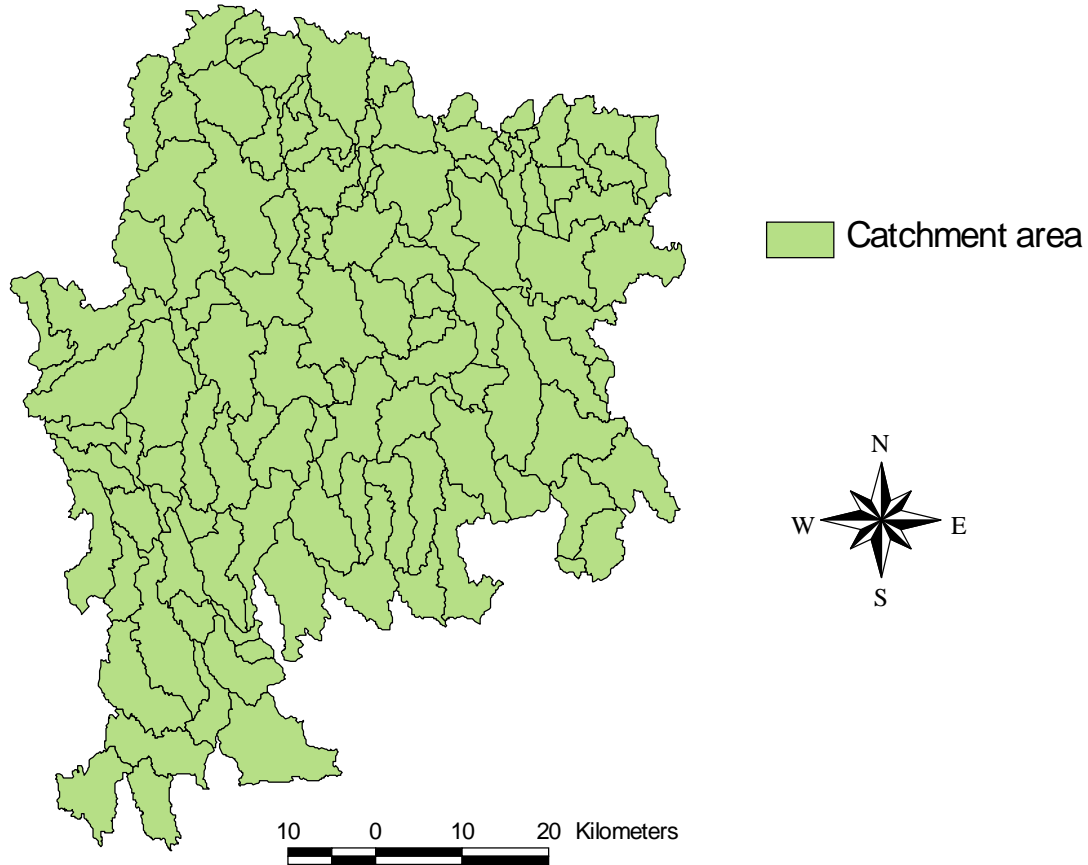
Figure 4. Catchment areas of Mälaren in the county of Västmanland

The calculations have been made for the Swedish county of Västmanland. In Figure 4 the catchment areas of Mälaren are shown with a mean sub catchment area of 34 km^2. The calculated chloride concentration is an average value for the recharge water in every sub catchment area. However, the chloride concentration in discharge water for a sub catchment area is a function of the concentration in recharge in the area and the concentration in water from areas upstream the basin [1].

$$[Cl]_i = \frac{\frac{M_{Cl}}{M_{NaCl}} \sum \left(\frac{m_{salt}}{(P-E)A} + [Cl_{dep}] \right)_i A_i}{\sum A_i} \qquad [1]$$

Result

In Västmanland the annual net recharge varies between 200 and 300 mm, and the background deposition contributes to a chloride concentration of 2 mg/l in recharge water. In Figure 5 the average calculated chloride concentration in recharge is shown for all sub catchment areas of Mälaren within the county of Västmanland. The amount of deicing salt applied (in tonnes per kilometre and season) for the different road categories is 12 tonnes for A2, 11 tonnes for A3, 4 tonnes for B1and 1 tonne for B2. There are no A1 or A4 roads within the county.
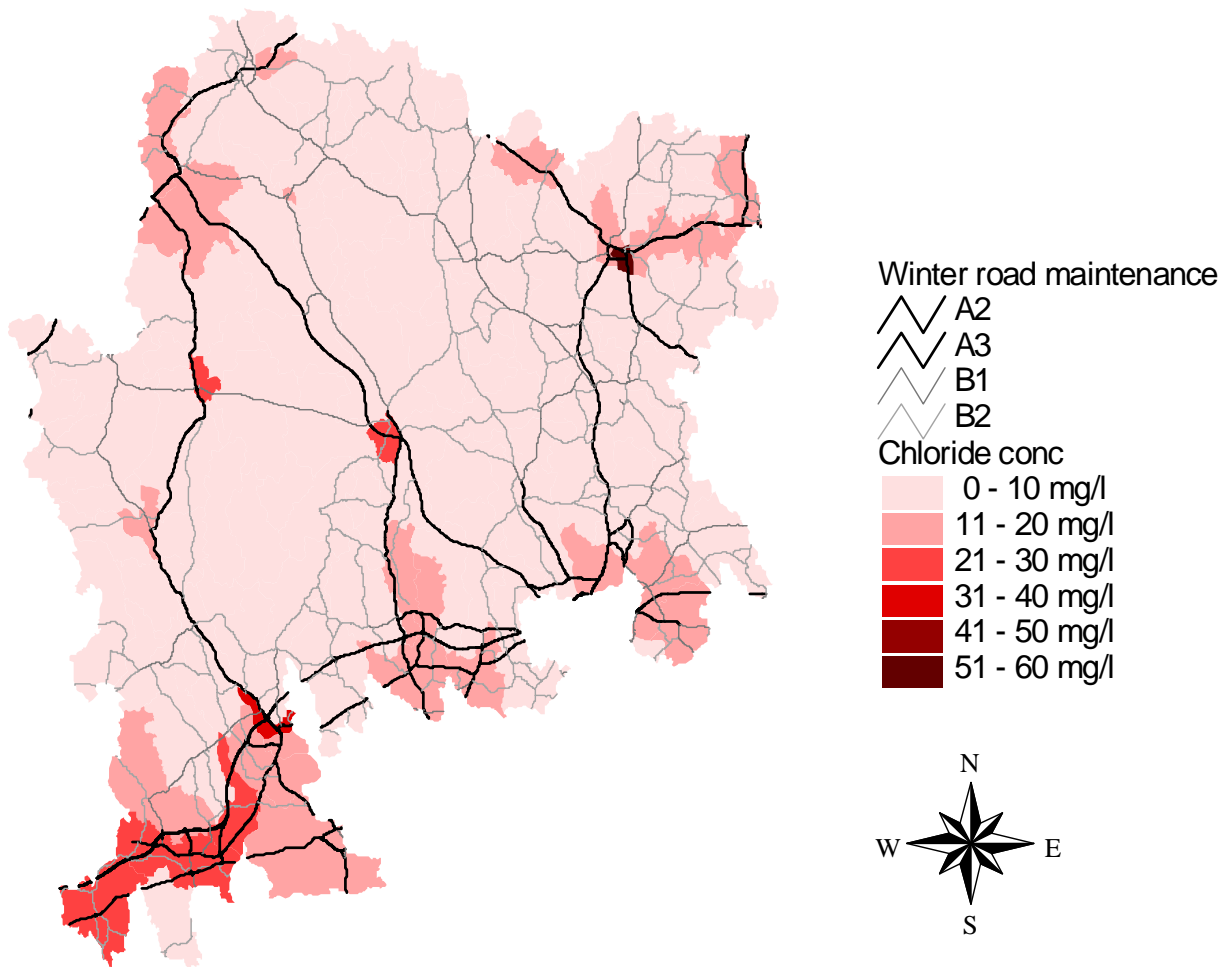
Figure 5. Average chloride concentration in recharge water in sub catchment areas in Västmanland, Sweden.

Discussion

The method shows the environmental effect of deicing salt application on a larger scale. The seasonal variations and the local spatial variations may influence the actual concentration. To calculate the average steady state concentrations is to simplify a complex event in order to estimate the effects.

Originally the calculations were county based. However, in order to calculate concentrations in a particular sub catchment area the calculation must begin at the watershed and hence, the calculations were change to be catchment area based. As mentioned above the calculated chloride concentration is an average value for the recharge water in every sub catchment area and the chloride concentration in discharge water for a sub catchment area is a function of the concentration in the recharge in the area and the concentration in water from areas upstream the basin. In reality the closest representation of this value would be the chloride concentration in a lake or in a large spring close to the outflow from the sub catchment area. As a part of the National Monitoring Programme, the SLU University in Uppsala investigates the status of some lakes every fifth year. In the three most recent investigations the chloride concentration has been measured. In order to evaluate the method, the calculated chloride

concentration in each sub catchment area was compared to the measured chloride concentrations in lakes close to the outflow from the respective sub catchment area. The calculated chloride concentration was consistent with the measured values.

Another possible way to appreciate the effects of deicing salt is to start with measured values and estimate the contribution from other sources. How large is the contribution from road salt compared to other sources of chloride (e.g. relict salt, saltwater intrusion, sewage, landfills, fertilisers etc). The presented method only considers deicing salt application and background concentration. Other sources may be of equal or larger importance locally. However, the greatest impact of deicing salt may be for areas where the chloride concentration already is increased due to other factors.

In order to estimate the chloride concentration with more precision it is necessary to consider the direction of the water flow. Upstream a road only fresh water will infiltrate or form runoff. Immediately downstream the road the chloride concentration in infiltrating water or surface water will be the highest. The location of the road within the catchment area will be of importance for the obtained chloride concentration. If the road is located further downstream the dilution effect will be much greater than if the road is located "higher up" in the system with only a small amount fresh water contribution.

The contamination will be quite high fore small areas with many major roads. If the area is "higher up" in the system, the concentration in discharge water from the area will be high. If the area is closer to the outlet the dilution effect may reduce the concentration to lower levels.

When calculated chloride concentrations are compared with the measured concentrations especially in urban areas it is important to remember the differences in urban and rural environment. In the rural environment the road can be considered a line source. In the urban environment the use of deicing salt is more evenly distributed since not only the Swedish National Road Administration but also municipal and private property owners use salt for deicing purposes. Hence is it more accurate to consider the average application in g/mm^2 (Howard & Haynes 1993). Furthermore the amount of paved surfaces and the drainage water system in an urban environment will affect the water distribution within the catchment area.

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