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Biotechnol. Agron. Soc. Environ. 2017 **21**(2), 131-145

OPEN ACCESS

Identification of sprinkling storage facilities for windblown timber using a GIS-based modeling approach

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Received on May 20, 2016; accepted on April 18, 2017.

Description of the subject. After catastrophic storm events, the storage of windblown timber is an effective measure for mitigating economic losses in the forest sector by preventing wood decay, protecting stands from secondary damage, and regulating the timber supply in the middle and long term.
Objectives. In this study, we first propose a GIS-based methodology for identifying suitable sprinkling storage terminals in Wallonia (Belgium). In addition, we suggest an approach for building a coherent regional network as well as methods for selecting and activating terminals within this network after a storm, depending on the severity and distribution of the damage.
Method. The GIS-based approach was used to crosscheck technical requirements related to sprinkling storage according to operational and environmental constraints in the Ardenne, which is the most forested sub-region of Wallonia. A three-step process was employed to identify suitable areas. Nine procurement areas were also delineated according to the regional forest inventory plots as a reference for choosing the terminals that should be included in the regional network and activated after the storm.
Results. We generated and evaluated 96 scenarios. In the second step, a network of 30 terminals was suggested, which corresponded to a storage capacity of 4 million m^3. This network could facilitate the flexibility in the strategic management of storage after huge storms. The procurement area approach also helps addressing routing and transportation issues in a simple way.
Conclusions. The GIS approach facilitates the selection of sprinkling storage terminals, but field validation and enhanced collaboration between public and private landowners and forest owners would still be needed.
Keywords. Geographical information system, risk management, timberyards, wind damage, Belgium.

Une approche SIG pour planifier à l'échelle régionale le stockage sous aspersion de bois chablis

Description du sujet. Lors de tempêtes de grande ampleur, le stockage rapide des chablis sous aspersion permet de limiter les pertes financières pour la filière forêt-bois en freinant la dépréciation qualitative des bois chablis, en limitant les risques phytosanitaires concomitants pour les peuplements sur pied et en permettant de réguler, à moyen et à long termes, l'approvisionnement des industries.
Objectifs. Dans cet article, nous proposons une méthodologie basée sur un système d'information géographique (SIG) en vue d'identifier un réseau de sites potentiels de stockage sous aspersion en Wallonie (Belgique).
Méthode. Un modèle SIG a été utilisé pour croiser les exigences techniques relatives au stockage sous aspersion avec des contraintes opérationnelles et environnementales pour le cas spécifique de l'Ardenne, zone la plus boisée de Wallonie. Des zones d'approvisionnement homogènes ont aussi été délimitées pour faciliter la sélection des sites et leur activation après tempête.
Résultats. Un réseau de 30 sites potentiels de stockage, correspondant à une capacité totale de 4 millions de m^3, a été identifié. Ce réseau permettrait une grande flexibilité dans la gestion stratégique du stockage, notamment en matière de répartition de la capacité et d'optimisation des couts.
Conclusions. Ce réseau est en théorie adapté à la problématique du stockage de bois chablis à l'échelle régionale, il reste nécessaire de procéder à une validation sur le terrain des sites et d'élaborer un protocole de collaboration entre les propriétaires fonciers et forestiers publics et privés.
Mots-clés. Système d'information géographique, gestion du risque, chantier forestier, dégât dû au vent, Belgique.

1. INTRODUCTION

Severe winter storms are major threats to forests throughout the world (Van Lierop et al., 2015) and they are considered to be the most destructive abiotic agent for European forests (Thom et al., 2013). In particular, storms originating from extra-tropical cyclonal processes that generate maximum wind speed gusts above 30 $m \cdot s^{-1}$ are likely to cause extensive damage to forest resources (Gardiner et al., 2010). The frequency and intensity of storm events are likely to increase in mid-latitudes in continental regions within this century (Leckebusch et al., 2006), and higher surface wind speeds (Fink et al., 2009) with shorter return periods (Karremann et al., 2014) are also expected in Central and Western Europe. This upward trend in windstorm severity combined with the increasing exposure of forests due to the accumulating standing timber volume in Europe (Seidl et al., 2011) will increase the risk of severe winter storm losses in future decades (Schwierz et al., 2010).

Windstorms may destroy the equivalent of several annual harvests within a few hours (Bründl & Rickli, 2002; Björheden, 2007). In planted and intensively managed forests, where the economic value at risk is high, such sudden disturbances often cause the collapse of timber prices (Nieuwenhuis & O'connor, 2001) and owners may suffer drastic financial losses (Moore et al., 2013), which can be exacerbated by the increasing costs of timber salvage (Prestemon & Holmes, 2004) and stand restoration (Schönenberger, 2002). Imbalances in timber availability after huge storms propagate through the industrial supply chain and affect market dynamics (Schwarzbauer & Rauch, 2013). Every economic agent within the forest-wood chain is affected and they must adapt their procurement behavior (Hartebrodt, 2004). In most cases, public funds provide compensation for only a minor proportion of the economic losses incurred (Brunette & Couture, 2008). However, in addition to their economic effects, destructive storms also have environmental and societal consequences, where they may threaten the delivery of forest goods and services to society (Seidl et al., 2013). For instance, wind disturbances can offset national carbon storage strategies that rely on forest sinks (Lindroth et al., 2009). Regardless of the perspective, the integrated management of storm risk is required at the regional and/or national level(s) to support the entire forest-based economy (Riguelle et al., 2016).

Among the possible mitigation measures that are available to decision makers in the aftermath of destructive storms, timber storage has been employed as an effective approach for reducing the impacts on the timber market during previous crises (Grayson, 1989; Peralta et al., 1993). Indeed, storms affect timber prices through their volume and quality (Brunette et al., 2012), so storage could have a double positive effect (Costa & Ibanez, 2005). First, by preserving the technological quality of timber that cannot be processed quickly, storage can mitigate the economic losses for owners and industry. Second, timber storage can help to regulate the supply over a longer time-scale and limit the volatility of prices. It can also contribute to reducing atmospheric carbon releases (Zeng et al., 2013) and decrease phytosanitary risks by limiting the exposure of still standing and healthy trees to pest outbreaks. The most common method for storing timber and preventing its degradation by fungi or insects involves saturating the logs with water, either by sprinkling or ponding, in order to maintain their moisture contents above a threshold value of 100%, and then keeping this saturation level constant throughout the storage period (Peralta et al., 1993).

However, several issues must be considered when planning timber storage before and after a storm. Among the strategic issues, we need to consider the basic choice between storage and exportation (Caurla et al., 2015), the amount to store by species, and the duration of storage. Decision support tools may help decision makers to assess the effects of storage on the dynamics of the windblown timber supply chain (Riguelle et al., 2015). There are also numerous operational issues to consider, including site preparation, the installation and maintenance of materials, caretaking for terminals, and requests for public authorization. In addition, tactical issues must be addressed, mainly logistics. The logistics of timber storage include inbound and outbound features, encompassing operations from damaged forest areas to terminals and from terminals to end-users (*e.g.* paper mills, sawmills, panel factories, energy plants). It also involves many operations and actors for moving, stacking, and managing timber products, as well as hiring and training people, which would be very expensive. For instance, extra costs ranging between 12 and 20 $EUR \cdot m^{-3}$ can be expected for sprinkling storage over a period of three years (Liese, 1984; Costa & Ibanez, 2005). Despite the financial compensation often provided by public subsidies, it is important to minimize these supplementary costs in order to ensure the cost-effectiveness of storage in the long term. Thus, economies of scale can be enhanced by limiting the number of terminals and increasing the amount stored per terminal (Costa & Ibanez, 2005). In addition, transportation accounts for a large proportion of the storage costs (Murphy, 2003; Audy et al., 2012a), so the distance that needs to be covered by trucks and loading characteristics are important factors that should be considered. In terms of other timber supply chain issues, the spatial arrangement of terminals with respect to transportation and infrastructure costs is a key challenge (Rauch & Gronalt, 2010; Kons et al., 2014). Nevertheless, it is necessary to integrate the requirements of all the end users as well as coping with the available road facilities and environmental constraints (*e.g.*, protected areas).

The level of preparedness before a calamity and the ability to react quickly after a storm event are further key challenges when trying to develop an efficient timber storage strategy. This is particularly true in countries and regions that have not been affected by severe storm damage for decades, where the storage infrastructure and related knowledge have disappeared gradually or have not been developed. This is the case in Wallonia – the southern region of Belgium – where the establishment of a regional storage strategy is now a priority for strengthening the storm damage risk management process (Riguelle et al., 2015). In this context, it is important to support public decision makers by identifying suitable locations for sprinkling storage terminals based on legal, technical, and operational criteria. Furthermore, it is necessary to help build a regional network of terminals that could be activated after a destructive storm, depending on the severity and distribution of the damage. Therefore, the present study had three main aims. First, we developed a model within a geographical information system (GIS) software for identifying suitable locations for sprinkling storage terminals. We then prepared a simple method for selecting a subset of terminals based on a homogeneous geographical delineation. Finally, we developed two decision approaches for selecting the terminals that can be used after a storm within the predefined network. We assessed and illustrated all of these methods based on a regional case study in Wallonia. We also discuss the relevance of these methods in the Discussion section.

2. MATERIALS AND METHODS

2.1. Study context

The proposed GIS methodology is illustrated based on the specific geographic scope of Wallonia in the South of Belgium (latitude-longitude minimum: 49°30’00”–6°24’00”; latitude-longitude maximum: 50°48’60”–2°52’48”; 16,844 km^2). Woodlands cover roughly 33% (555,000 ha) of Wallonia (**Figure 1**) and about 87% of these woodlands are dedicated to intensive timber production (Alderweireld et al., 2015). The overall annual harvest is roughly 4,000,000 m^3. The present study focused particularly on the Ardenne sub-region, which contains 64% of the regional growing stock (GS) and supplies 85% of the softwood timber, mainly spruce. Several factors contribute to the high level of wind damage risk within this area. First, the regional GS per hectare increased by 25% between 1984 and 2015 (Alderweireld et al., 2015), thereby exacerbating the regional exposure to windthrows. In addition, Norway spruce (41% of GS) and beech (9% of GS), which are species that are prone to wind damage (Schütz et al., 2006), are prevalent in the Ardenne. Spruce and beech wood have limited natural durability, so they should be stored rapidly after a storm in order to avoid further losses of quality and money.

Several timber industries that use round wood (logs or bolts) or byproducts (wood chips) as their raw

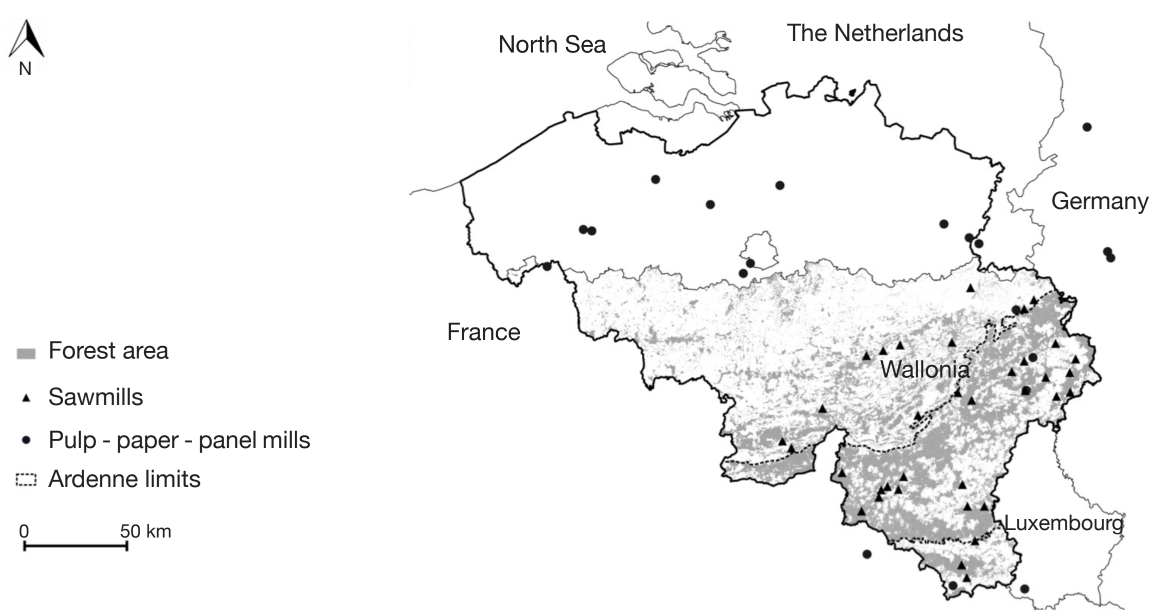

Figure 1. Forest area in Wallonia and major forest-based industries in Belgium and surrounding countries — *Surface forestière en Wallonie et principales industries du bois en Belgique et dans les régions avoisinantes.*

materials are located close to the study area. Sawmills are mainly located near the forest estates in order to limit transportation costs. According to regional statistics, 2,500,000 m^3 of softwood and 70,000 m^3 of hardwood are sawn each year. The Belgian pulp, paper, and panel (PPPs) sector consumes roughly 4.2×10^6 m^3 of timber per year (expressed in round wood equivalents) and logs comprise about half this amount. PPPs industries are mainly located near the regional borders or outside Wallonia. Hence, only 18% of the total procurement by PPPs normally comes from Wallonia, and the majority is mainly imported from France (67%) and Germany (7%).

2.2. Requirements linked to sprinkling storage

In this study, we focused only on sprinkling storage (spraying timber with water) because ponding (immersion of logs in water) is very infrequent in Wallonia. We used several descriptions of this storage process from previous studies (*e.g.*, Liese, 1984; Syme & Saucier, 1995; Pischedda, 2004; Latour et al., 2009) to determine the requirements that must be considered when identifying suitable locations for sprinkling storage terminals (**Table 1**). Geographic representations of these requirements were constructed using several original geodatasets in order to process them in a GIS model. The regional geodatasets used in the model are all accessible on an open-source basis, and these data have been validated as well as updated frequently by their provider.

A strategy for the establishment of sprinkling storage terminals in Wallonia must first consider land occupation. First, all the land-use types, including agricultural areas and woodlands, were considered as suitable from a technical viewpoint. However, areas closer than 100 m to residential areas had to be excluded to minimize annoyance for the surrounding population, and because authorizations and permits would not be granted by public authorities for these locations. Protected catchment, flood-prone, and bathing areas were also avoided due to the potential impacts of sprinkling storage runoff on both surface and ground water (Hedmark & Scholz, 2008). This implies the exclusion of many lakes and natural areas from selection because Wallonia contains most of the drinking water resources in Belgium. Protected natural areas cannot be used in order to avoid biodiversity losses. In addition, the soil type and topographic slope should be considered during the selection process. We also decided to exclude soils with poor drainage features (*i.e.*, hydromorphic or peaty soils) in order to ensure a minimal bearing capacity as well as to avoid damage to the soil structure and flora. We eliminated sloping grounds with a slope of more than 7% for operational reasons.

In addition, a set of relative size and accessibility criteria were considered. The regional road network was considered fully suitable for transporting timber, but highways were excluded because they do not allow direct access to the terminals. Watercourses characterized by a minimal watershed of 500 ha and inland water bodies of at least 500 m^2 were considered appropriate water supply sources. These features were assumed to guarantee the minimal water provision for sprinkling operations but without exhausting the water source (Elowsson & Liukko, 1995). Furthermore, terminals must have sides measuring at least 100 m in width and length to ease handling operations. Finally, we assumed that 10,000 m^3 would be stored per hectare on average, which corresponds to stacks of logs measuring 3 m in height and 10 m in length (Pischedda, 2004).

Table 1. Sprinkling storage requirements and associated original data sources — *Critères liés au stockage sous aspersion et sources de géodonnées originales*.

Requirement	Original data sources*	GIS layer	Type	Equivalent scale/resolution	Update
Protection of natural areas	Protected areas	RESNAT	polygons	1:10,000	2016
	Natura2000 sites	NAT_2K	polygons	1:10,000	2012
Protection of hydric resources	Water catchment zones	CATCH	polygons	1:10,000	2016
	Official bathing zones	BATH	polygons	1:10,000	2012
	Flood risk zones	FLOOD	polygons	1:10,000	2016
Restrictions due to land affectation	Sector plan	LAND	polygons	1:10,000	2016
Slope of storage terminals	Digital Elevation Model	DEM	raster	1x1 m pixel	2014
Soil features (bearing and drainage)	Digital Soil Map	CNSW	polygons	1:20,000	2008
Accessibility to road network	Regional road network	ROADNET	lines	1:10,000	2017
Accessibility to water supply	Watercourses	WCOURSE	lines	1:10,000	2010
	Water bodies	WBODY	polygons	1:10,000	2010

* Open-source data available on http://geoportail.wallonie.be

2.3. Identification of storage terminals

A GIS model was developed using the Model Builder module embedded in ESRI© ArcGIS 10.2 software. This module allows the creation, editing, and management of workflows, which string together sequences of geoprocessing tools, where the output of one tool is fed into another tool as an input. Thus, successive processes were chained together and recorded as a specific Spatial Analyst tool within the ArcTool Box. The GIS method can be described as three stages. In the first step, areas where sprinkling storage is technically and legally feasible are selected by combining the spatial constraints (**Figure 2** and **Table 2**).

The land-use layer (LUSE) reflects the land occupation due to regional legislation (LAND). A buffer is made to exclude areas closer than 100 m to residential areas. The slope values are derived from a digital elevation model of Wallonia (DEM), where the user must define the maximal slope to consider during selection at this stage (*slope_max*) before generating the intermediate output layer (SLOP). Appropriate soils (SOIL) are selected from a digital soil map of Wallonia (CNSW). The ECOL layer merges the limits of protected areas defined under the regional legislation (RESNAT) and sites from the Natura2000 network (NAT_2K), according to European Council Directive 92/43/EEC. The HYDR layer aggregates three elements comprising the protected catchment (CATCH), bathing (BATH), and flood risk zones (FLOOD). Excluding the DEM, the original data are vectorial and they must be converted into raster mode (*Feature to Raster* function) for the geoprocessing steps. The spatial resolution (pixel size) used in raster mode is 10 m.

In the second step, two intermediate layers (ROAD and WATE) are generated by a similar

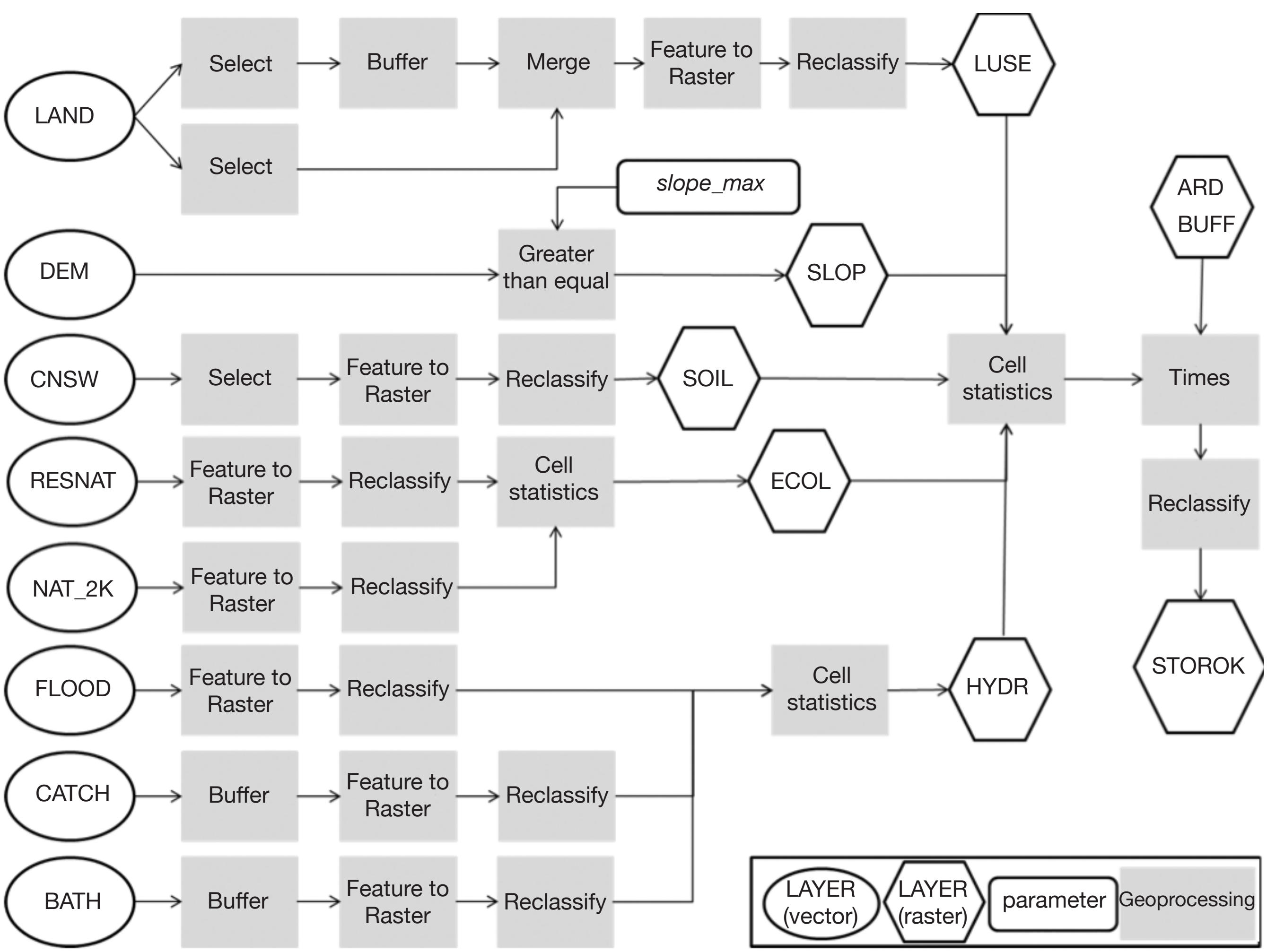

Figure 2. First stage of the GIS method: identification of areas suitable for sprinkling storage — *Première étape de la méthode GIS : identification des sites convenant au stockage sous aspersion.*

abbreviations — *abréviations*: see **tables 1** and **2** — *voir **tableaux 1** et **2**.*

Table 2. Pre-determined constraints and variables used in the terminal selection process — *Contraintes prédéterminées et variables intervenant dans le processus de sélection*.

Model input	Description	Pre-determined constraint	Variables
Layers			
ECOL	Ecological restrictions	Exclusion of protected areas	-
HYDR	Hydrological restrictions	Exclusion of catchment, flood-risk and bathing areas	-
LUSE	Land-use restrictions	Exclusion of areas close to residential zones (< 100 m)	-
ROAD	Appropriate accesses for trucks	Exclusion of highways	-
SLOP	Restriction to flat grounds	Exclusion of slopes > 7%	-
SOIL	Restriction to bearing soils	Exclusion of hydromorphic and peaty soils	-
WATE	Appropriate water sources	Watershed ≥ 500 ha, water bodies ≥ 0,5 ha	-
Parameters			
dist_road	Minimal distance to a road	-	100, 250, 500 or 1,000 m
dist_wat	Minimal distance to water source	-	100, 250, 500 or 1,000 m
site_area	Minimal area of terminals	-	2 or 5 ha
site_size	Minimal size requirements	Length and width ≥ 100 m	-
slope_max	Maximal slope	-	2, 5 or 7%

process (**Figure 3**). The input layers either contain the lines (ROADNET), or the lines (WCOURSE) and polygons (WBODY), which form the regional road and hydrographic networks. Based on these outputs, the model calculates the Euclidean distance between the center of a cell (pixel) and the closest road and hydrographic element. A selection is then made according to the maximal distance to the road network (*dist_road*) or water source (*dist_wat*) set by the user. The *Euclidean Distance* function allows the initial vectorial entities to be transformed into raster mode.

Finally, the outputs of the first and second stages are used in the third step to produce the ultimate selection of sprinkling storage terminals (**Figure 4**). Areas matching the technical and legal requirements (STOROK) are combined with accessibility criteria (ROAD and WATE) to identify potential storage terminals. The *Multipart to Singlepart* function is used

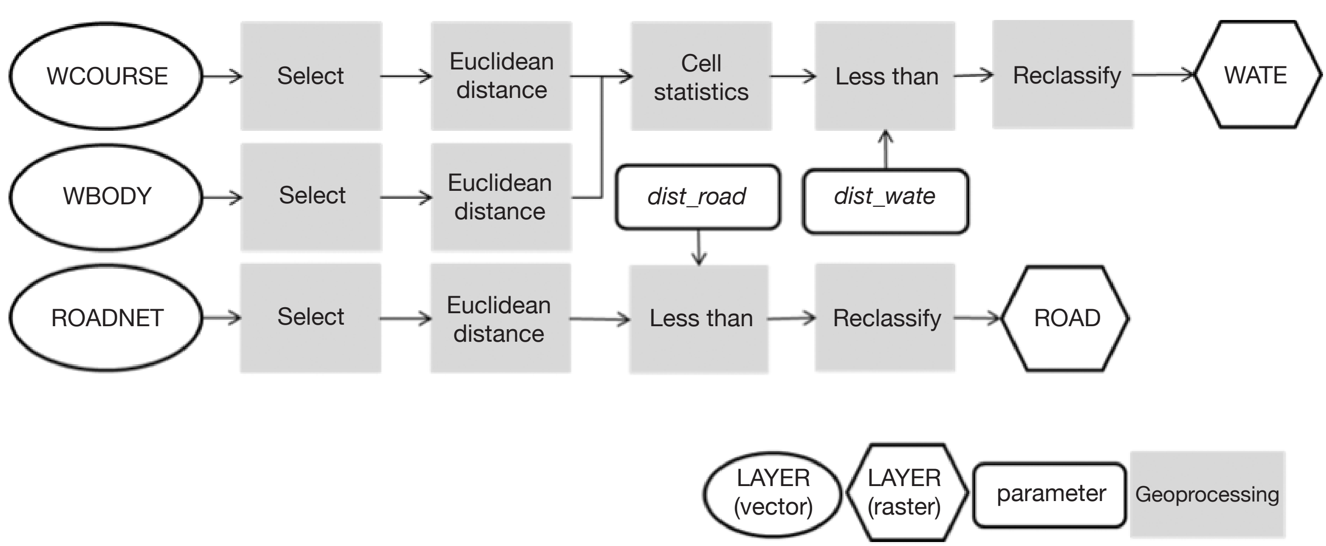

Figure 3. Second stage of the GIS method: accessibility to the road network and water sources — *Deuxième étape de la méthode GIS : accessibilité au réseau routier et à la ressource hydrique*.

abbreviations — *abréviations*: see **tables 1** and **2** — *voir **tableaux 1** et **2***.

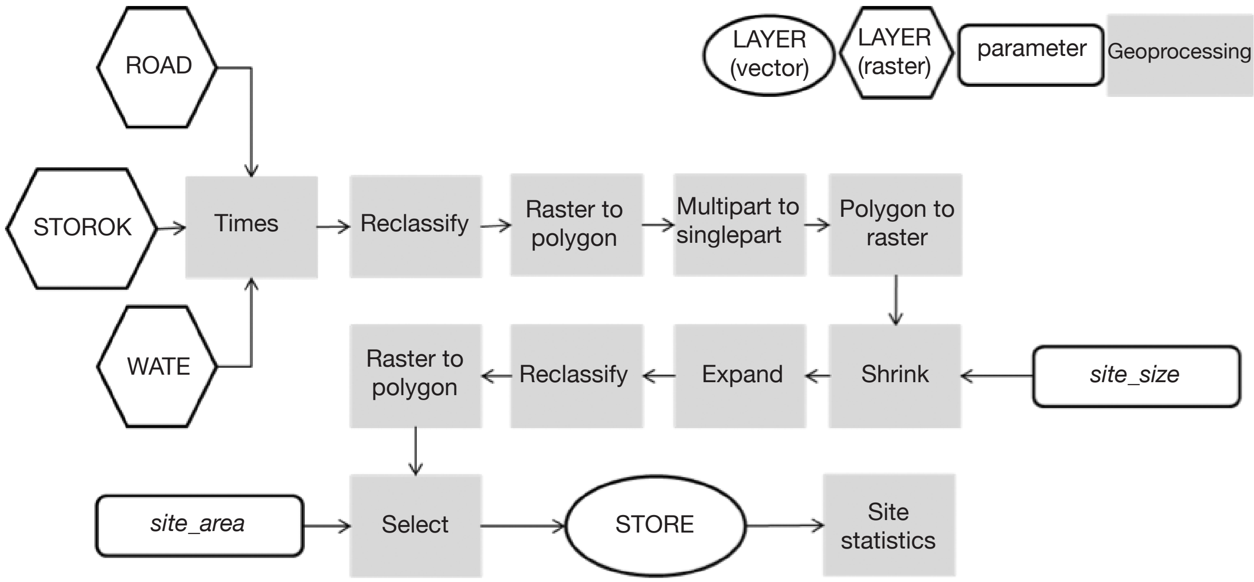

Figure 4. Third stage of the GIS method: selection of storage terminals — *Troisième étape de la méthode GIS : sélection des sites potentiels*.

abbreviations — *abréviations*: see **tables 1** and **2** — *voir **tableaux 1** et **2***.

to create single part features, which are generated by separating multi-part input features. In order to select terminals that satisfy the length and width criteria (100 m), polygons are changed again into raster mode and resampled to 100 m by 100 m using the *Shrink* function. Thus, terminals measuring less than 100 m in width and length are eliminated, whereas others are reestablished as initial choices with the *Expand* function (10 pixels). This operation also removes small amounts of erroneous data. A final selection process allows the elimination of terminals where the area is under the chosen threshold (*site_area*). For each entity in the resulting layer (STORE), the surface (ha), storage capacity (m^3), maximum slope (%), and distances to a road (m) and water supply (m) are calculated by the model (*Site Statistics* function).

The model integrates the predetermined constraints (see § 2.2.) but it is also possible to assign a range of values to four of the five parameters related to terminals size and accessibility (**Table 2**). Thus, three values (2, 5, and 7%) can be assigned to the slope, four different values (100, 250, 500, and 1,000 m) can be selected for the minimum distance to a road (*dist_road*) and water supply source (*dist_wat*), and storage areas with minimum areas of 2 and 5 ha can be selected (*site_area*). Thus, the user can model up to 96 different combinations of criteria. This particular feature allows the identification of relationships and the mutual influences between criteria in order to select different scenarios to reach the regional storage target (*e.g.*, in terms of the number of terminals or overall capacity).

2.4. Definition of a regional storage terminal network

We also developed an approach for selecting a subset of sprinkling storage terminals and creating a regional network that can be put into operation before a future storm. The term network highlights the individual contribution of each terminal to the global storage effort. Even if terminals are not linked "physically", they should be considered as intrinsic elements that contribute to the overall storage capacity. There are two possible ways of making the final selection of terminals. The first involves using the less restrictive scenario as a starting point and selecting all potential terminals that meet the criteria defined by users (*e.g.*, capacity, distance to road or water, slope, and number of sites), which can be achieved using a multi-criteria decision making method for weighting criteria and selecting the best-ranked sites. However, this method does not guarantee an optimal spatial distribution of terminals. The second approach, which we developed in this study, is based on a preliminary delineation of the regional territory into smaller homogeneous zones, from which terminals are selected among a limited number of scenarios.

Thus, the first step in this sub-selection process involves defining sub-regional areas to control the distribution of terminals throughout the territory and limiting the maximum transportation distances. Nine procurement areas (PAs) were delineated in the Ardenne (**Figure 5**). In this study, delineation was made

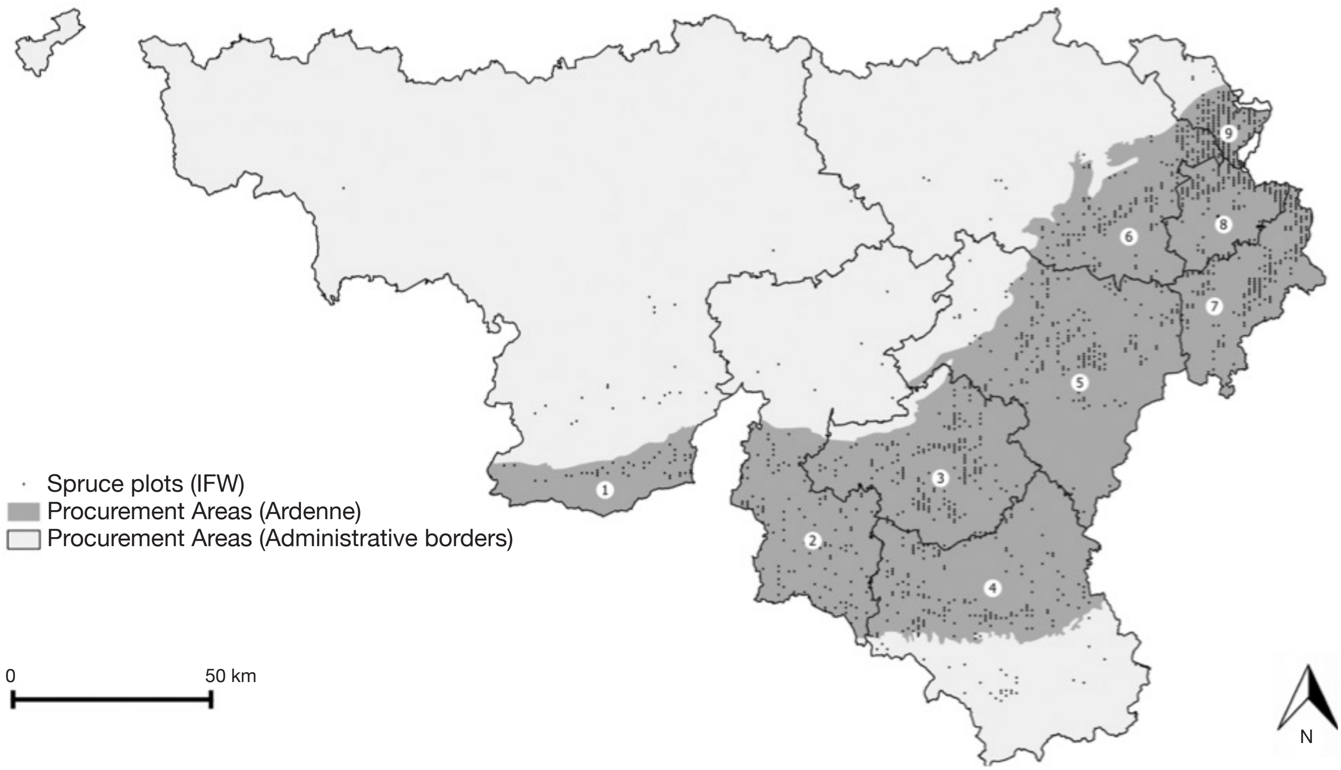

Figure 5. Procurement Areas and IFW plots where spruce is the dominant species in Ardenne sub-region — *Découpage en Zones d'Approvisionnement et présence de placettes avec dominance d'épicéa en Ardenne.*

under the assumption that PAs must be homogeneous in terms of both the timber availability and probability of damage. This assumption implies that each PA would generate a similar amount of windblown timber in the case of a wide-scale storm. Thus, we used the regional forest inventory (IFW), which is a systematic network of 11,000 sampling plots located in public and private estates in Wallonia. In particular, we used the public plots where spruce (a wind-sensitive species) is the dominant species (41% or 1,315 plots) and we generated iterative geographic breakdowns to obtain the most equal repartition of plots (around 11%) among the nine PAs. The limits of the 33 administrative districts of the regional forest service were considered as the smallest possible borders in order to ease administrative and operational management of the terminals. Therefore, most of the PAs contained between 9% and 14% of the IFW sampling plots where spruce was the dominant species (**Table 3**). Except for PA1, which was limited by country boundaries, the PAs were globally homogeneous in terms of their exposure to damage, and thus in terms of the probability of wind damage assuming similar wind speed and climatic conditions for the whole Ardenne region.

In the second step, the user has to select a limited number of combinations (scenarios). In this study, three criteria were set as priors for this pre-selection process:

Table 3. Sample rate of regional inventory (IFW) and spruce density by Procurement Area (PA) — *Taux d'échantillonnage de l'inventaire forestier wallon (IFW) et densité de l'épicéa dans les Zones d'Approvisionnement (PA).*

PA	IFW public plots		IFW spruce plots		Spruce plots density
	Total	%	Total	%	%
1	231	7	42	3	18
2	578	18	128	10	22
3	575	18	190	14	33
4	542	17	163	12	30
5	360	11	186	14	52
6	359	11	174	13	48
7	253	8	172	13	68
8	161	5	137	10	85
9	170	5	123	9	72
TOTAL	**3,229**	**100**	**1,315**	**100**	**41**

the number of sites (minimum 30), the total capacity (minimum 2.5 million m^3), and the mean capacity per terminal (above 50,000 m^3). The selected scenarios were then merged, duplicates were suppressed, and terminals were added to the selection for each PA, starting with the largest. The selection process ended when the target capacity was reached. In Wallonia, the maximum storage capacity has been evaluated as around 4,000,000 m^2 (Riguelle et al., 2016). This target is assumed to offer sufficient flexibility in terms of the choice of active terminals at the regional level after a storm.

2.5. Activation of storage terminals after windstorms

As mentioned earlier, a common issue for public decision-makers after a severe storm is determining the terminals that should be activated within the pre-established network in order to meet the strategic storage target. Thus, we developed and assessed two decision-making methods based on the damage severity and distribution for the Wallonia context. Both methods use the territorial breakdown into PAs as the basis for selection. In the first step, the amount of damage assessed at a regional scale must be disaggregated for each PA. In Wallonia, the level of damage was evaluated by a method based on the IFW within a 72-h delay period (Riguelle, 2010). This procedure can be used in the terminal activation process to determine the sub-geographical repartition for damage in each PA (PA_{DAM}). In addition, a storage target is determined at the strategic level. This target is expressed as a percentage of the estimated damage and it is then applied to each PA to determine the amount to store locally (PA_{MIN}). Finally, the terminals are chosen according to two repartition methods, as follows.

The first repartition method (*balance*) aims to obtain a balanced repartition of terminals at the regional level. In each PA, terminals are selected successively from the biggest to the smallest until the storage target is reached. The underlying rationale is that the distance between forests and terminals should be minimized during the first months after a storm when the transportation capacity is often lacking and more expensive. In the second method (*maximization*), the goal is to completely fill the terminals, again from the biggest to the smallest regardless of their localization, assuming that the pre-selection of terminals according to the regional delineation (PA) should guarantee a homogeneous repartition. In this case, the objective is to limit the number of terminals and increase the amount stored per terminal for cost-efficiency purposes. In both selection processes, the amount stored in each PA cannot exceed the damage in the area and the damaged timber located on one side of a PA boundary can be transported to a terminal on the other side of the area.

3. RESULTS

3.1. Identification of storage terminals

According to the range of values tested for the slope (*slope_max*), site area (*site_area*), distance to water supply (*dist_wat*), and road network (*dist_road*), 96 sets of potential terminals were generated using the GIS-based modeling process. **Figure 6** provides an overview of the effects of these criteria on the selection process in terms of the number and size of sprinkling storage terminals. The less restrictive combination of criteria, *i.e.*, an area of 2 ha, slope of up to 7%, and roads and water within a radius of 1,000 m, identified more than 3,000 suitable zones occupying 50,000 ha. The overall storage capacity obtained in this scenario comprised more than 500 million m^3. The mean capacity was 160,000 m^3 per site but there were actually many small zones. However, in 36 scenarios, no suitable sites could be found in the study area because when the maximum slope was set to 2%, the minimal area was 5 ha and the maximum distance to the road network was 500 m. No terminals were found on steeper fields (5 and 7%) near the road network (≤ 100 m). The slope factor clearly affected the number of areas selected for sites of both 2 and 5 ha. There were more potential terminals when the slope was higher. This relationship was clearly influenced by the characteristics of the topography in Ardenne. However, the slope was a limiting factor when searching for bigger terminals (5 ha), especially in proximity to the road network. A maximal slope value of 5% appeared to provide a good tradeoff because it allowed the identification of sufficient terminals and storage capacity, irrespective of the distance to the road network and water sources. It was also logical to find more terminals of 2 ha compared with terminals of 5 ha when using the same combination of criteria. Nevertheless, the average storage capacity (or mean area) was always superior for scenarios based on a threshold of 5 ha, which can be explained by the geoprocessing resolution merging adjacent sites of less than 5 ha into a unique site of more than 5 ha.

The number of potential terminals decreased dramatically as the maximum distance to a water supply reduced, which implies that fewer areas were available close to water sources. However, the mean area of the terminals did not decrease as dramatically, and it would be possible to store more than 100,000 m^3 per terminal on average at a distance of 250 m from water sources. This supports the fact that larger areas can be found in alluvial plains than more hilly landscapes. Finally,

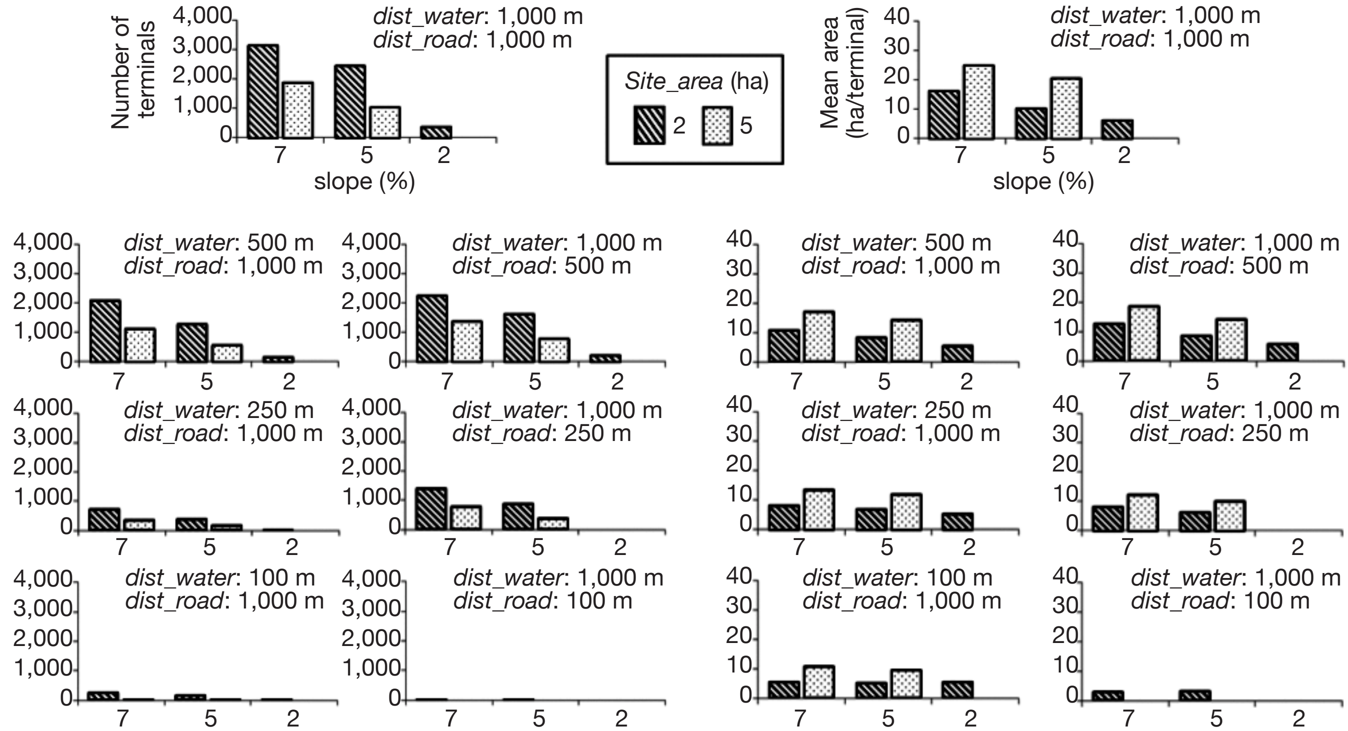

Figure 6. Influence of criteria (*slope_max*, *site_area*, *dist_wate*, *dist_road*) on the results in terms of number and size of sprinkling storage terminals — *Influence des critères de sélection des sites (*slope_max, site_area, dist_wate, dist_road*) sur les scénarios en termes de nombre et de superficie*.

the distance to the road network also influenced the selection. Numerous areas were suitable for timber storage up to a threshold distance of 250 m, whereas very few sites were available below this threshold due to the ribbon-type of urbanization along many roads in Wallonia. The comparison of scenarios did not identify an optimal combination that minimized the access distances and the slope as well as maximizing the size of the terminals. Therefore, the definition of the optimal set of terminals implies tradeoffs in terms of the major requirements of decision-makers.

3.2. Proposal of a sprinkling storage network for Wallonia

The output of the network selection procedure is presented in the following. In order to screen the scenarios initially, we selected the terminals with a minimum of 5 ha and a maximum slope of 5%. Next, we minimized the distance to water sources (maximum 250 m). In the second step, we performed sorting according to three strategic constraints (see § 2.4.): minimum number of 30 terminals, total capacity above 2.5 million m^3, and mean capacity per terminal greater than 50,000 m^3. Four scenarios matched these selection criteria (**Table 4**). However, the set identified in scenario 59 was actually a subgroup of the terminals selected in scenarios 55 and 52.

The two selected scenarios were merged (85 entities) and duplicates were eliminated. We conducted manual selection among the remaining terminals (60 entities). This final screening process was guided by three assumptions:
- locations should minimize the distance between woodlands and terminals as well as terminals and forest-based industries;
- terminals should be distributed homogeneously across the PAs;
- the storage capacity within each PA should be proportional to the repartition of the IFW's spruce plots for the PA.

The result comprised a regional network containing 30 terminals with an overall storage capacity of 4 million m^3 (**Figure 7** and **Table 5**). The mean and median capacities were 133,000 m^3 and 123,000 m^3, respectively.

3.3. Activation of storage terminals in a windthrow crisis context

In order to determine the sites that should be activated within the network, we applied the two repartition methods (*balance* and *maximization*) to the previously identified regional network of 30 terminals, where we assumed homogeneous damage of 8 million m^3 at the

Table 4. Scenarios matching with sub-selection criteria (number > 30; total capacity > 2.5 million m^3; mean capacity > 50,000 m^3/site; site_area = 5 ha; slope_max = 5%) — *Scénarios correspondant aux critères de sélection (nombre > 30 ; capacité totale > 2,5 million m^3 ; capacité moyenne > 50 000 m^3/site ; site_area = 5 ha ; slope_max = 5 %).*

Characteristics						Parameters			
Scenario	Number of sites	Total area (ha)	Total capacity (Mm^3)	Mean area (ha/site)	Mean capacity (m^3/site)	*site_area* (ha)	*slope_max* (%)	*dist_wate* (m)	*dist_road* (m)
51	**47**	**446**	**4.5**	**9.5**	**95 000**	**5**	**5**	**100**	**1,000**
52	174	2,064	20.6	12	120 000	5	5	250	1,000
55	108	1,069	10.7	10	100 000	5	5	250	500
59	**38**	**284**	**2.8**	**7.5**	**75 000**	**5**	**5**	**250**	**250**

In bold, the two scenarios selected to build the regional network — *En gras, les deux scénarios sélectionnés pour construire le réseau.*

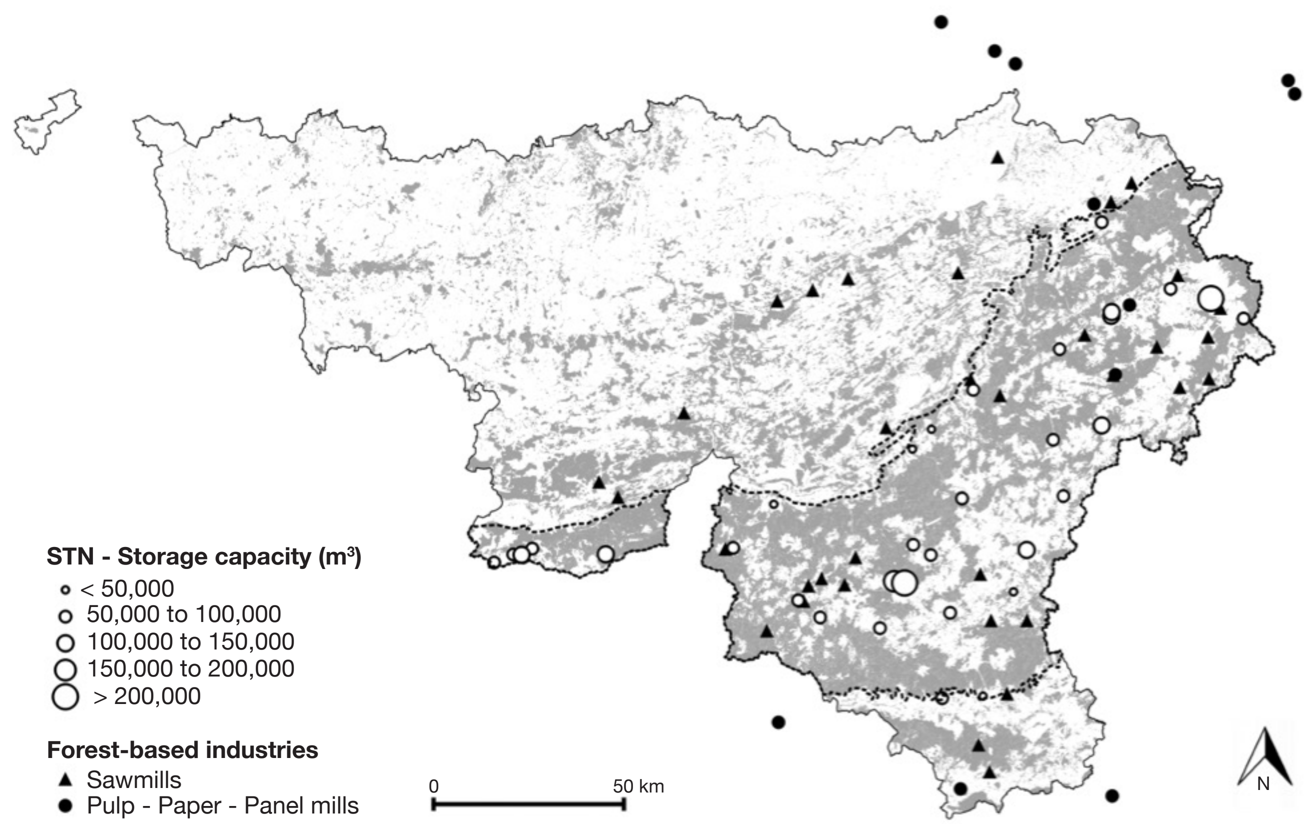

Figure 7. Suggested locations of a sprinkling storage terminals network (STN) in Wallonia and proximity to forest-based industries — *Localisation potentielle d'un réseau de sites de stockage (STN) de bois sous aspersion en Wallonie et proximité des industries de la filière bois.*

regional scale, which is similar to the impact of storm Vivian in Wallonia in 1990. This amount corresponds to twice the regional annual harvest and 7% of the regional GS. A storage target of 2 million m^3 was set in order to prevent a quarter of this supply from suddenly entering the timber market. The results are presented in **figure 8**.

Balanced repartition finally selected 14 terminals scattered across the PAs, where only five were completely filled. Thus, the global capacity used only reached 75%. However, the higher density of terminals at the regional scale decreased the mean transport distance within the network. In the optimized process, nine bigger terminals were selected and completely filled, but 16% of the capacity was still available in the ninth terminal. Globally, 98% of the mobilized storage capacity was used, thereby maximizing the volume stored per area. The geographical locations were not

Table 5. Storage capacity by Procurement Areas (PA) — *Capacité de stockage dans chacune des Zones d'Approvisionnement (PA).*

PA	Number of sites	Storage capacity (m^3)	Capacity share (%)	IFW spruce plots (%)
1	2	217,400	5	3
2	3	356,625	9	10
3	4	477,390	12	14
4	4	500,000	13	12
5	5	576,800	14	14
6	5	549,525	14	13
7	2	525,675	13	13
8	3	442,140	11	10
9	2	357,675	9	9
TOTAL	**30**	**4,003,230**	**100**	**100**

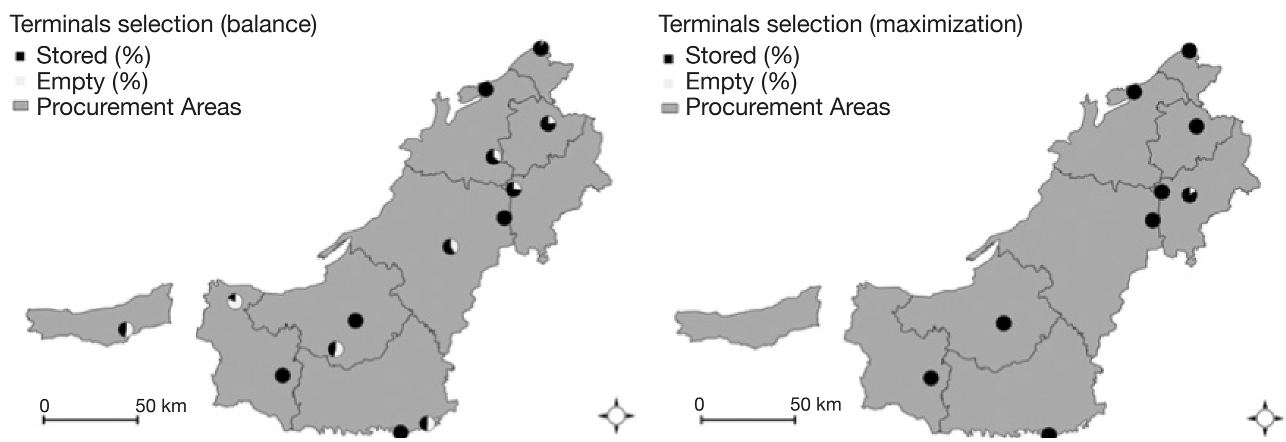

Figure 8. Activation of terminals in Ardenne sub-region after a storm, aiming to balance the spatial distribution (left) or maximize the capacity stored in terminals (right) — *Activation des sites de stockage en Ardenne après tempête : à gauche, répartition spatiale équilibrée (13 sites) ; à droite, maximalisation du volume stocké par site (9 sites).*

considered in the selection process but because the high-capacity terminals were distributed homogeneously in the Ardenne due to the PA delineation method, at least one terminal was selected in every PA, except for PA1.

4. DISCUSSION

In this study, we developed a framework and methods to facilitate the implementation of a windblown timber storage strategy at a regional level. The aim was to develop simple methods to support decision making by public authorities and the forest-based sector before and after a future damaging storm. The GIS-based model developed in this study allows the identification of sprinkling storage terminals that satisfy a set of legal and operational constraints, which are based on open-source data that have been validated and updated frequently. The model is accessible and the parameters (constraints and variables) can be set easily thanks to the features of ArcGIS Model Builder.

The results showed that there are many suitable locations for sprinkling storage terminals in the Ardenne sub-region, thereby providing a potentially high storage capacity. The slope threshold clearly affected the number of areas selected, where the potential terminals were more numerous when the slope threshold was higher. However, the slope was a limiting factor when searching for bigger terminals (5 ha), especially in proximity to the road network. The number of terminals also decreased dramatically as the maximum distance to a water supply reduced. This supports the fact that larger areas can be found in the alluvial plains rather than in the more hilly parts of the

Ardenne. The distance to the road network also affected the selection. However, generating and comparing scenarios did not determine an optimal combination that minimized the access distances and the slope as well as maximizing the size of the terminals. Thus, the definition of the optimal set of terminals still requires further tradeoffs by decision makers.

To address the latter limitation, we developed an approach based on geographical delineation (PAs) in order to define the network. The approach based on PAs is limiting because it does not encompass other risk components, such as the storm intensity and trajectory, the economic value at risk, and the susceptibility of stands to damage, but it allows the rapid identification of terminals. The terminals could be selected based on a "site quality index", which may combine site characteristics such as the capacity, distance to a road network or water supply, and slope. Multicriteria decision-making approaches can help by assigning relative values to these parameters and ranking the terminals. However, a homogeneous repartition of terminals throughout Wallonia could not be guaranteed using this approach. From a strategic perspective, the network developed in this study also facilitates flexible storage management after huge storms. Indeed, decision makers would need sufficient options to adapt the regional storage strategy according to repartition and the severity of damage. Furthermore, the final selection of sites during storm crisis management could be facilitated by using one of the two repartition methods. Again, there is no unique way of activating the terminals and both approaches may be valid depending on the context.

We used ArcGIS software to support the selection of terminals but the overall terminal selection process was not fully automated. Manual selection was still needed at some stages, but this did not appear to be an issue for users. It should also be noted that the results were pre-validated by checking their coherence with topographic maps and satellite imagery. Nevertheless, it will be necessary to perform field validations to support the results, especially if the original geodatasets were not updated recently. For instance, there could be discrepancies between the GIS outputs and reality, such as changes in watercourse tracks or land-use changes (mainly urbanization). In addition, the selected locations should be assessed on a case-by-case basis in order to avoid financial side effects, *e.g.*, if highly valuable stands are selected as suitable areas.

In addition, other issues must be considered. For instance, as shown by previous crises, timber transportation is probably one of the key logistical issues that need to be addressed after severe storms. The capacity for transportation is often lacking after a storm (Bourcet et al., 2008) due to the limited availability of trucks and road legislation. Public authorities are bound to increase the transport capacity to avoid a major bottleneck in timber mobilization at the regional level, but they will make changes according to a global strategy, *e.g.*, for storing or exporting timber (Caurla et al., 2015). Furthermore, the optimal routing of round wood between storage terminals and industries is required to limit transportation costs (Bergdahl et al., 2003). Thus, decision support systems based on Dijkstra's algorithm for finding the shortest path could assist decision makers with optimizing transportation flows (Forsberg et al., 2005; Andersson et al., 2008). Timber bartering or backhauling (Carlsson & Rönnqvist, 2007) are also important considerations if the transport capacity is lacking. In the absence of this type of approach, the use of PAs as sub-regional storage management units could be an easy way of addressing routing and transportation issues.

After a severe storm, the main challenge for industries is adapting rapidly and securing their supply chains according to new market conditions (Björheden & Helstad, 2005). Again, decision support systems based on operations research models can help industrial users to identify new strategies, including timber storage in terminals (Epstein et al., 2007; Broman et al., 2009). However, the logistic plans of companies must be changed over the course of a few days to ensure procurement, so the storage conditions should be known in advance, and thus a predefined regional storage strategy may be desirable. In addition, the involvement of industries in the storage effort, which would be conditioned by the costs of operations, is also crucial for the success of the public strategy. In this context, we consider that collaborative logistics within the forest-based sector would definitely be crucial for reducing storage and transportation costs (Frisk et al., 2010). However, as shown by Audy et al. (2012b), a framework is required to implement collaboration between regional stakeholders and public authorities should actively contribute toward its definition, especially if they mainly fund storage operations, *e.g.*, addressing the central issue of stocking and destocking logs belonging to several owners without financial prejudice. It will also be necessary to check the financial feasibility of processes with owners.

5. CONCLUSIONS

In conclusion, GIS-based approaches can help to increase the preparedness of decision makers from both public and industrial perspectives regarding future storm events. Nevertheless, the pro-active management of operational issues (such as permits and facilities) is necessary to guarantee the rapid implementation of a storage strategy. Furthermore, in the context of an integrated storm crisis management process, collaboration among stakeholders within the forest-based sector is undoubtedly crucial for reducing storage and transportation costs, as well as for making a storage strategy advantageous to all. A timber storage strategy must be viewed in this context as part of an integrated and systematic management process developed at the regional level to alleviate the impacts of storms on the forest-based sector.

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