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REVIEW

Water management: global differences and similarities in guidelines for forest road design and potentials for climate change adaptation

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Abstract

Forests roads follow standardized design protocols which utilize unpaved gravel to ensure rapid water drainage but also leaves them prone to erosion. However, in many places, precipitation patterns are significantly affected by global climate change. The design of forest roads should be adapted to these changing conditions, which requires a fundamental understanding of current design standards. This systematic literature review was intended to examine the state of the practice by analyzing 32 guidelines from 26 regions worldwide for 46 design features (parameters) significant for drainage and water management. The review was conducted in three phases: identifying relevant design features and categorizing them into six groups (alignment, cross-sectional profile, side slopes, ditches, ditch relief structures, and water crossings), examining their regional specifics and similarities, and discussing climate change adaptation potentials. Several parameters were found to be uniform and in agreement across the analyzed guidelines e.g., the use of a crowned cross-sectional profile and "V"-shaped ditches, the dimension and orientation of cross-culverts. In contrast, some design guidelines included additional or conflicting parameters, such as the discharge of surface runoff water from ditches into streams or riparian buffer zones, and the use of "U"-shaped ditches. Future studies should prioritize the identified key parameters, such as the spacing of ditch relief structures, the choice of ditch type, riparian buffer widths, and dimensions of stream crossings, to develop designs that are well proven and easily adaptable under changing climates. The results of this review can provide a foundation for improving road design practices to mitigate the impacts of climate change.

Keywords Forest Infrastructure · Water management · State of practice · Drainage · Climate change adaptation · Road engineering

Introduction

Forest road systems play an important role in managing forests worldwide (Dutton et al. 2005; Sessions et al. 2007; Petkovic and Potočnik 2018). Forest road systems are critical to the wood supply chain which is reliant on feeder and wood haul roads. Haul roads, which are especially intended for year-round truck traffic, fulfill additional social, economic, and ecological functions, e.g., providing accessibility to forest ecosystems for firefighting or recreational purposes (Hentschel 1999; FAO 2017).

In many regions of the world these low-volume roads are built as unpaved gravel roads, which makes them susceptible to erosion by water (Kraebel 1936; Arnáez et al. 2004; Cao et al. 2021). Therefore, it is critical to ensure prompt drainage of water following precipitation events in order to prevent damage and maintain their operability. To address water drainage while mitigating erosion, forest roads show design features such as elevated cross-sectional profiles and ditches or ditch relief structures including culverts and waterbars. There is however evidence that these structures can significantly interfere with the natural water regimes, e.g., by increasing the amount and rate of water discharge from ecosystems (Ziegler and Giambelluca 1997; Wemple and Jones 2003; Toman 2004; Soulis et al. 2015). Additionally, sediment discharge into streams is often linked to the presence of forest roads and can be mitigated by best

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management practices such as frequent ditch and culvert maintenance, installation of adequate water crossings and culverts, and stabilization of slopes (Kraebel 1936; Grace 2002b; Grace and Clinton 2006; Aust et al. 2015).

Considering the changing global climate and associated impacts on water regimes, additional challenges are faced along unpaved gravel roads. Climate change has already altered and will continue to alter the frequency of extreme precipitation events and the severity of droughts in many regions (IPCC 2023). This makes it increasingly important to retain road runoff water in adjacent ecosystems, thereby reducing the risk of flooding and increasing the amount of available water for nearby plants. In addition, damages to the roads can likely be reduced by adapting road designs. This integrated concept, referred to as "road water harvesting" or "green roads", has been discussed in various studies (Demenge et al. 2015; Gebru et al. 2020) and summarized by Steenbergen et al. (2021). Measures include, for example, redirecting runoff to surrounding areas or reducing connections between ditches and streams. While the primary focus of these concepts is on agricultural use of the harvested water in arid and semi-arid regions, the approach can also be adapted for forest infrastructure. In this way, negative effects of climate change on the water balance (Fig. 1) in forest ecosystems can most likely be mitigated.

However, this requires a fundamental understanding of the state of practice of forest road design with respect to drainage and water management. Design standards of forest roads worldwide are outlined in legislation, guidelines, and handbooks. These are intended to assist practitioners in planning and construction of adequate roads which meet the local requirements. In addition, they can include strategies for minimizing environmental impacts or measures for maintaining road quality.

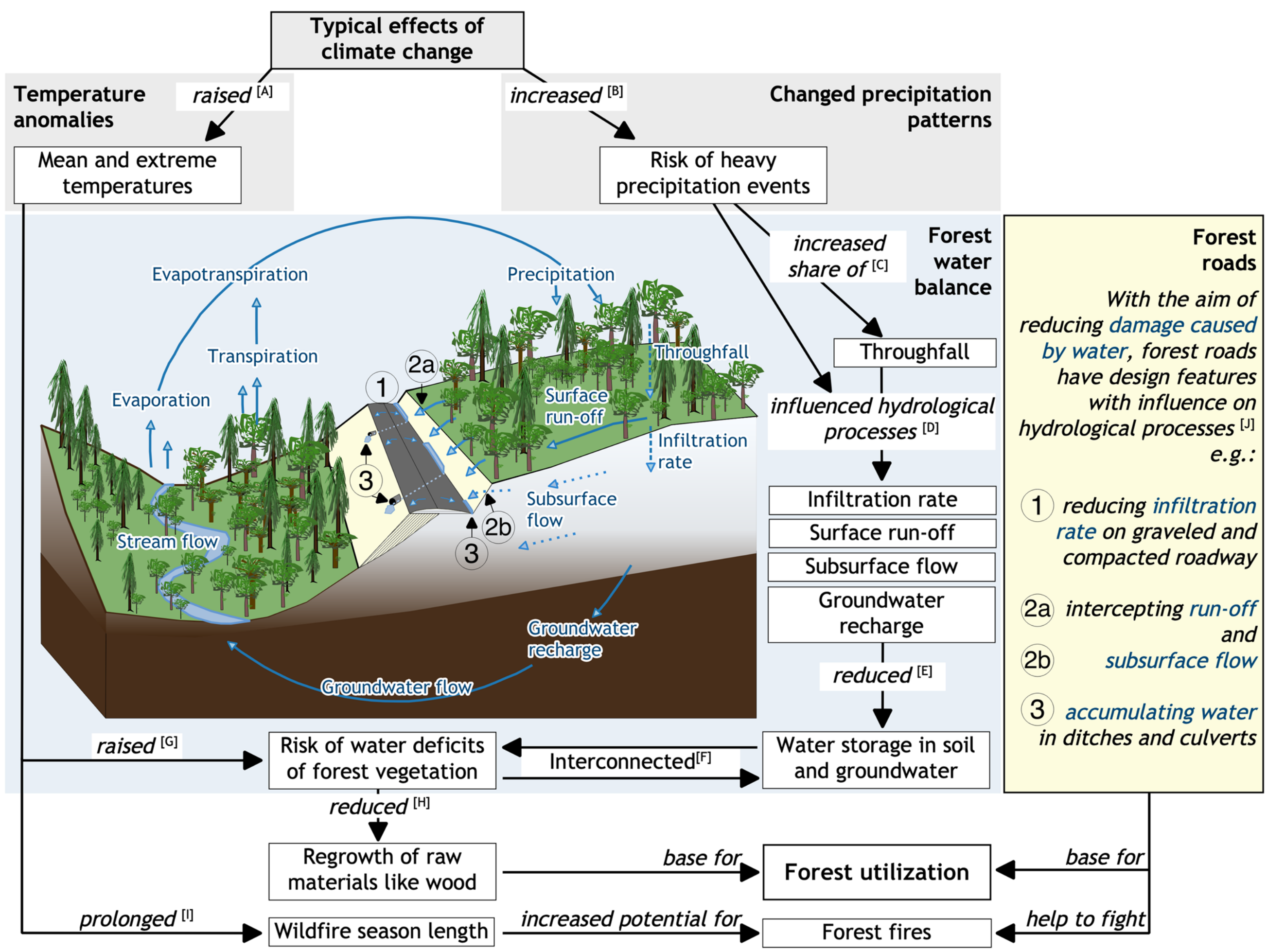

Fig. 1 Selected interactions between forest roads, climate change effects, water management and forest utilization. Sources for marked processes/interactions: [A] = Meinshausen et al. (2017), [B] = Martel et al. (2021); Ham et al. (2023), [C] = Crockford and Richardson (2000), [D] = Zhang et al. (2016); Sleziak et al. 2021; Corona et al. (2023), [E] = Tillman et al. (2020), [F] = Condon et al. (2020), [G] = Grant et al. (2013); Dai et al. (2018); Kupec et al. (2021), [H] = Gholz et al. (1990); Mantgem et al. (2009), [I] = Camia et al. (2016); Wuebbles et al. (2017); Jones et al. (2022), [J] = Dutton et al. (2005); Soulis et al. (2015); Kastridis (2020)

In order to contribute to the goal of adapting water management along forest roads to mitigate the effects of climate change, we aim to provide an understanding of the current state of practice. To this end, we (1) compiled a list of 46 parameters relevant for drainage and water management, (2) identified typical practices in water management along forest roads from 32 guidelines from 26 regions worldwide, and (3) discuss the potentials for climate change adaptation in road engineering under consideration of both historical and contemporary scientific literature.

Material and methods

Review strategy

A systematic review following the approaches outlined by Carrera-Rivera et al. (2022) was carried out in three phases, each addressing interconnected research questions:

1st phase: Relevant design features (parameters) critical for drainage or with a potential connection to water management were identified by investigating guidelines and the available scientific literature. A list of parameters was formulated in the first phase and broader categories separating the parameters were formed.

Research question: *What design features of graveled forest roads are important for drainage and water management?*

2nd phase: This phase involved the establishment of a cross-table, where the analyzed sources from legislation, guidelines, and handbooks were represented as columns and the identified parameters (1st phase) as rows. This table allowed for a systematic extraction and comparison of the data from the guidelines.

Research question: *How is water management and drainage along graveled forest roads implemented worldwide? What are the differences and similarities?*

3rd phase: The cross-table was discussed under consideration of the scientific literature with the objective to identify the parameters with the greatest potential for adaptation to mitigate the effects of climate change.

Research question: *Is there evidence in global design guidelines and scientific literature of potential for adaptation to climate change in water management along graveled forest roads?*

The study relied on different sources to gather relevant information: Databases including *Scopus*, *Google Scholar*, and the *CABI library "Forest Science Collection"* were searched for peer-reviewed articles. Guidelines were searched by using search engines such as *Google* and *Bing*, as well in the library of the *Department of Forest Work Science and Engineering* in Göttingen, Germany.

Once the literature was collected, duplicate entries from different databases were removed and the following in-/exclusion criteria were applied to identify relevant source documents:

- **Languages**: Sources in English, German, and Italian were included.
- **Time frame**: Even with the focus on current climate change, no temporal limits were set, given that the construction and drainage of gravel roads has been practiced for millennia. This ensured the inclusion of both historical and contemporary perspectives.
- **Accessibility**: Both open-access and commercially available publications were considered to ensure a broad spectrum of sources.
- **Guidelines:** Only sources explicitly addressing gravel roads, graveled forest roads, or water management along such roads were included, with preference given to region- or landform-specific materials.
- **Scientific literature**: Complementary research dealing with topics about gravel roads, graveled forest roads or water management along them was investigated.

Design features and their importance for water management

Description of forest roads and parameters

Since low-volume forest roads typically integrate modern engineered structures (e.g., concrete bridges, steel culverts, compacted pavements to achieve the required bearing capacity, or complex slope stabilization methods) with landscape-adapted design (e.g., unpaved gravel and narrow curve radii), the description of the system is highly complex, but can be achieved by characterizing it by design features. Different approaches can be found in the literature for specific sets of design features (parameters), e.g., ditch relief culverts (Eck and Morgan 1986; Piehl et al. 1988) or slopes (Borga et al. 2005; Jeong et al. 2021) or with different focusses like geometric design of highways (AASHTO 2018). However, to our knowledge, there is currently no systematic list summarizing forest road design features that affect drainage or water management. Therefore, we formulated the following catalogue (Fig. 2) to address the 1st phase of our review: *What design features of gravel forest roads are important for drainage and water management?*

We used a two-stage structure for this 1st phase of the review. In the first stage, we divided the parameters into areas or properties of the forest road. The categorization was based on existing classifications in the sources themselves, e.g., the roadway, alignment or drainage structures. In this stage of the review, we categorized six sets of parameters:

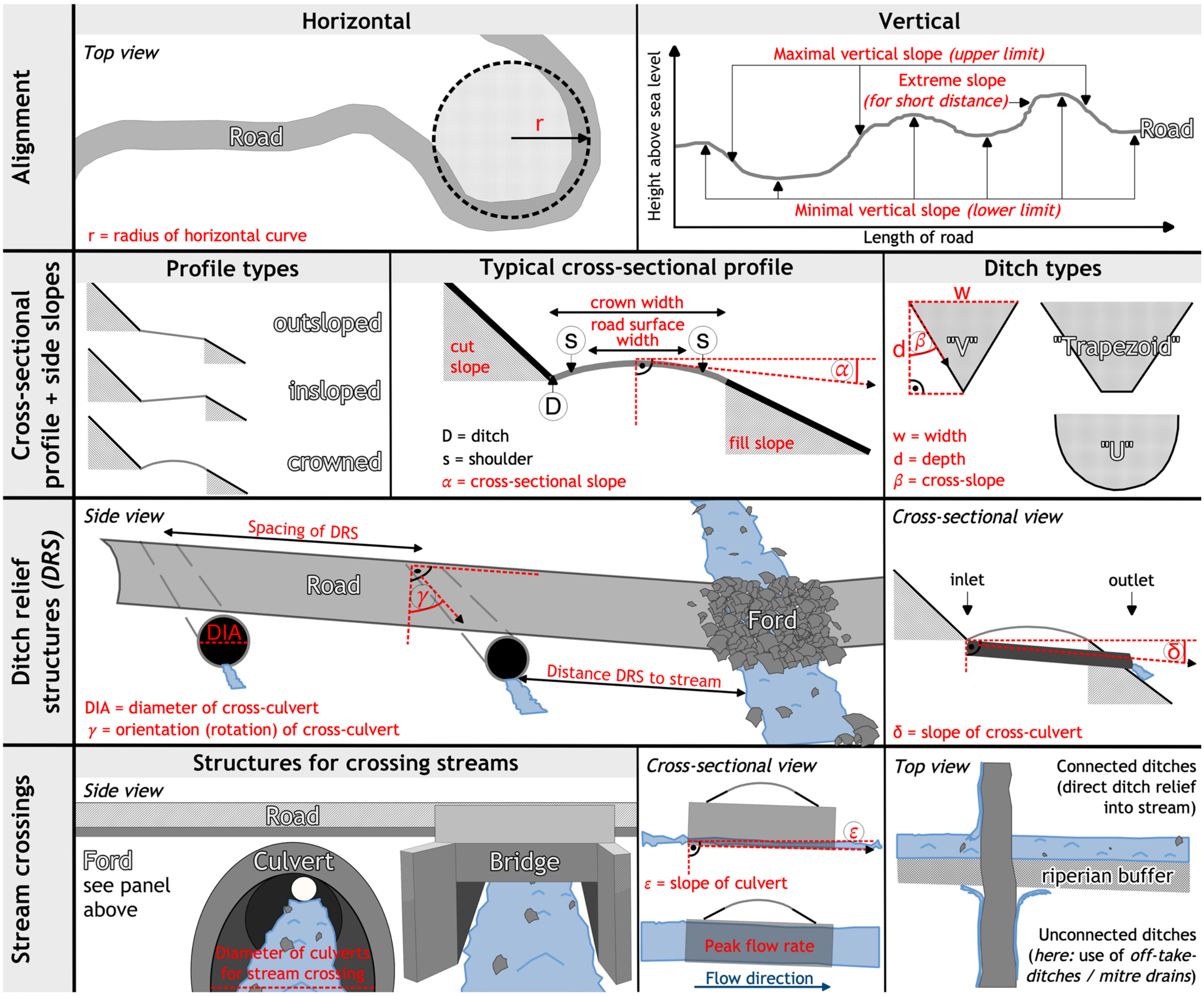

Fig. 2 Schematic overview. Parameters analyzed with significance to water management and drainage of forest roads

alignment, cross-sectional profile, side slopes, ditches, ditch relief structures, and stream crossings.

We then differentiated two further groups in the second stage. Firstly, 33 quantifiable parameters included, for example, upper and lower limits for vertical and horizontal alignment, as well as minimum diameters that must be met when installing cross-culverts. Secondly, 13 categorical variables were summarized, such as the recommendation of certain types of ditches or the use of fords for crossing streams. These parameters may have values such as "recommended", “not recommended”, "not specified", meaning the intended use of structures or approaches instead of numerical values (Table 1).

Even if qualitative characteristics were not a stated aim of the analysis, these were nevertheless included in several places to provide a holistic picture of the various approaches. For example, some sources recommended formulae for calculating the optimal ditch relief structure spacing, described how to mark culvert inlets in the field, or explained the estimation of peak flows for culvert and bridge sizing in detail. These examples cannot all be shown in this review, but examples are presented in suitable places.

Alignment

Alignment as a category of design features can characterize the course of more complex three-dimensional road using two numbers, namely horizontal and vertical alignment. Both the horizontal as well the vertical alignment cannot be looked at separately as, for example, drainage of water or driving speed are depending on the combination (AASHTO 2018). Still, there are important linkages, e.g. the potential for damage from erosion rises with increasing inclination. In contrast, the risk of road

Table 1 Analyzed forest road design parameters with categorization, units and corresponding keywords

Type	Number	Parameter		Unit	Keywords
Alignment					
Quantitative	1	Extreme	Road gradient (for short distance)	%	Alignment, vertical, horizontal. slope, grade, operating speed, geometric design, radii
	2	Upper limit for	Road gradient		
	3	Lower limit for	Road gradient		
	4	Narrowest horizontal curve		m	
	5	Design speed		km h^{-1}	
Cross-sectional profile					
Categorical	1	Recommendation for	Crowned profile Insloped profile Outsloped profile		Slope, cross-section, crown, inslope, outslope
Quantitative	6	Upper limit for	Cross-sectional slope	%	
	7	Lower limit for	Cross-sectional slope		
	8	Upper limit for	Crown width	m	Width, road dimension, right-of-way
	9		Road width		
	10	Lower limit for	Crown width		
	11		Road width		
Side slopes					
Categorical	2	Side slopes stabilization	With berm With compaction With drainage With fascine With gabion With geotextiles With riprap With vegetation		Side slopes, fill slope, cut slope, stabilization, berm, fascine, gabion, geotextiles, riprap, vegetation
	3	Side slopes stabilization structures examples			
Quantitative	12	Upper limit for	Cut slope	%	
	13		Fill slope		
Ditches					
Categorical	4	Recommendation for	Ditch type “armored” Ditch type “trapezoid” Ditch type “U” Ditch type “V”		Ditch form, ditch type, ditch depth, ditch width, dimension, drainage
Quantitative	14	Upper limit for	Vertical ditch gradient	%	
	15	Lower limit for	Vertical ditch gradient		
	16	Upper limit for	Cross-slope of ditch		
	17	Upper limit for	Ditch depth	m	
	18		Ditch width		
	19	Lower limit for	Ditch depth		
	20		Ditch width		

Table 1 (continued)

Type	Number	Parameter		Unit	Keywords
Ditch relief structures					
Categorical	5	Inventory of ditch relief structures			Ditch relief structure, cross-drainage, cross-culvert, buffer strip, riparian zone, off-take ditch, side slopes, spacing, mitre drain, wing-ditch, diversion, turnouts, formula, equation
	6	Discharge of water from the ditch into the stream			
	7	Spacing: Consideration of	Alignment Culvert dimension Erosion Local knowledge Maintenance Precipitation Upstream area		
	8	Recommendation of	Mitre drains/ off-take-ditches		
	9	Examples of structures for	Outlet armoring		
Quantitative	21	Upper limit for	Slope of cross-culverts	%	
	22	Lower limit for	Slope of cross-culverts		
	23	Upper limit for	Spacing of ditch relief structures	m	
	24	Lower limit for	Spacing of ditch relief structures		
	25	Lower limit for	Spacing of ditch relief and stream		
	26	Lower limit for	Width of mitre drains		
	27	Lower limit for	Diameter of cross-culverts	mm	
	28	Upper limit for	Rotation of cross-culverts	°	
	29	Lower limit for	Rotation of cross-culverts		
Stream crossings					
Categorical	10	Consideration of climate change for crossings			Stream, water crossing, culvert, bridge, ford, peak flow, return period, rational formula, talbot formula
	11	Examples for stream crossings			
	12	Recommendation	Of a formula for crossings Of rational formula for crossings Of talbot formula for crossings		
	13	Recommendation for stream crossings with fords			
Quantitative	30	Upper limit for	Slope of stream crossing culverts	%	
	31	Lower limit for	Slope of stream crossing culverts		
	32	Lower limit for	Diameter of stream crossings	mm	
	33	Advised return periods for estimated peak flows		a	

softening and with that the likelihood for potholes to develop will rise if the road gradient is level without possibility for water drainage (Lienert 1983). Even though no direct relation of design speed, minimal horizontal curve radius and management of water is given, the parameters were checked for understanding the design of forest roads in the analyzed regions as these are interconnected to other design features such as cross-sectional profile (Donnell et al. 2009; AASHTO 2018).

Cross-sectional profile and road width

The cross-sectional profile, and thereby also the width of the road, is the third component used to describe forest roads. The width of the road or the crown determines how much area is taken up by the road surface and thus affects surface runoff. By building wider roads, the potential for any kind of interference with the natural water flow will be higher, but wider roads also allow for higher vehicle speeds (Donnell et al. 2009).

Cross-sectional profiles are also relevant to water management. As with alignment, road surface softening can occur when water remains on the surface for long periods, especially in combination with a low gradient (Eck and Morgan 1987). Typically, the cross-sectional slopes (cross-slopes) of unpaved roads are more pronounced or noticeable than paved road surfaces (AASHTO 2018), which is why we investigated the upper and lower limits for cross-slopes.

Usually, there are three types of profiles: first, the outsloped profile, where the road is sloped downwards relative to the adjacent hill or mountainside. This allows water to drain downhill (i.e., exterior). The insloped profile in contrast will drain water towards the mountainside (i.e., interior), generally into ditches. The third profile is the crowned profile. Precipitation that falls on the exterior side of the road will be drained directly over the fill slope towards adjacent forest stands below, while the interior side of the road drains into a ditch.

Side slopes

Faulty design of cut and fill slopes and missing vegetation can have a negative influence on road stability and cause soil loss through erosion (Grace 2002a; Seutloali and Beckedahl 2015; Jalali et al. 2022). Rainfall simulations showed that the cut slope is particularly at risk of erosion (Arnáez et al. 2004). For mitigating potential failure, different measures such as gabions, compaction, and geotextiles can be taken to stabilize steep slopes (Grace 2002a; Liu et al. 2014; Solgi et al. 2021). For this reason, we investigated the upper limits for grading cut and fill slopes, and structures for ensuring slope stability.

Ditches

The absence of adequate ditches with appropriate dimensions or functionality may result in road overflows. During heavy rainfall, costly damages, such as washouts, can occur at such locations. Additionally, softening of underlying base layers can result in plastic deformation of the road. Poorly designed ditches can likely be eroded and increase sediment yield, especially when connected directly to streams (Forman and Alexander 1998; Jones et al. 2000; Lang et al. 2017). Therefore, it is important to ensure that ditches have sufficient discharge capacity and are frequently maintained (Brady et al. 2014). Our analysis included information on different types and dimensions of ditches (Fig. 2: “V”, Trapezoid, “U”, and width, depth, and cross slope, respectively), as well as the alignment of ditches.

Ditch relief structures

As water accumulates in the ditches, it should be regularly cross-drained to prevent accumulation of run-off resulting in softening and erosion damage to the road itself. Various structures can be used for this purpose, e.g., culverts, mitre drains and water bars. In the late 1980s, extensive research was carried out in the Appalachian Mountains to decide between two of these structures in terms of economy and performance (Eck and Morgan 1986, 1987). These investigations showed advantages of culverts over broad-based dips under most conditions (ibid.). A similar preference was given in the sources analyzed, which is why we also focused on culverts as cross-drainage structures in this review.

When using culverts as ditch relief structures, numerous criteria should be considered (Piehl et al. 1988). Firstly, the minimal diameter, which should be met during installation. Culverts with smaller diameters tend to become clogged with material or have insufficient drainage capacity. However, costs increase significantly with diameter and therefore culverts should not be oversized, which means that the minimum culvert diameter should comply with local drainage volumes. In addition to the minimal diameter, the cross-drainage structures should be installed within a reasonable distance so that water is not accumulated over long sections (ibid.). Some of the sources provided detailed information on spacing cross-drainage structures with respect to road gradient or other criteria. Furthermore, considerations such as the orientation (rotation) of the culvert below the road or the lower and upper limits of the culvert slope between inlet and outlet should be kept in mind. For simplifying maintenance of ditch relief culverts, marking of inlets can help to find the culvert even under vegetation. Different approaches for realizing the marking were investigated too.

Water crossings

Crossings of streams or rivers can be achieved by using structures like fords, culverts, or bridges. Typically, culverts are used for crossing smaller streams in forests. As construction of these structures can be complex and expensive, their discharge capacity and thus their size is usually adjusted to the expected water volumes with the help of hydraulic calculations (O'Shaughnessy et al. 2016). Among other factors, the catchment area and return periods of the estimated peak flows are included (Norman et al. 2001). While global climate change proceeds and water regimes are altered, it is expected that peak flows will be increased and return periods of these peak flows will be shortened (Poelmans et al. 2011; Surfleet and Tullos 2013; Kay et al. 2021; Martel et al. 2021). We therefore examined whether the sources contained any indications or further instructions of how to deal with the projected effects of climate change.

Assessment of potential for climate change adaptation

Adaptation to climate change requires the ability to modify the underlying design or implementation of the design to suit changed local or regional conditions (Smit et al. 1999). We argued that it is primarily quantitative parameters that show a wider range in use conditions that should be considered adaptable. Narrow use ranges suggest that the investigated design features are stricter and should be implemented similarly under all conditions, since they are determined, for example, by physical or mechanical constraints. While quantitative features were evaluated based on their variability or

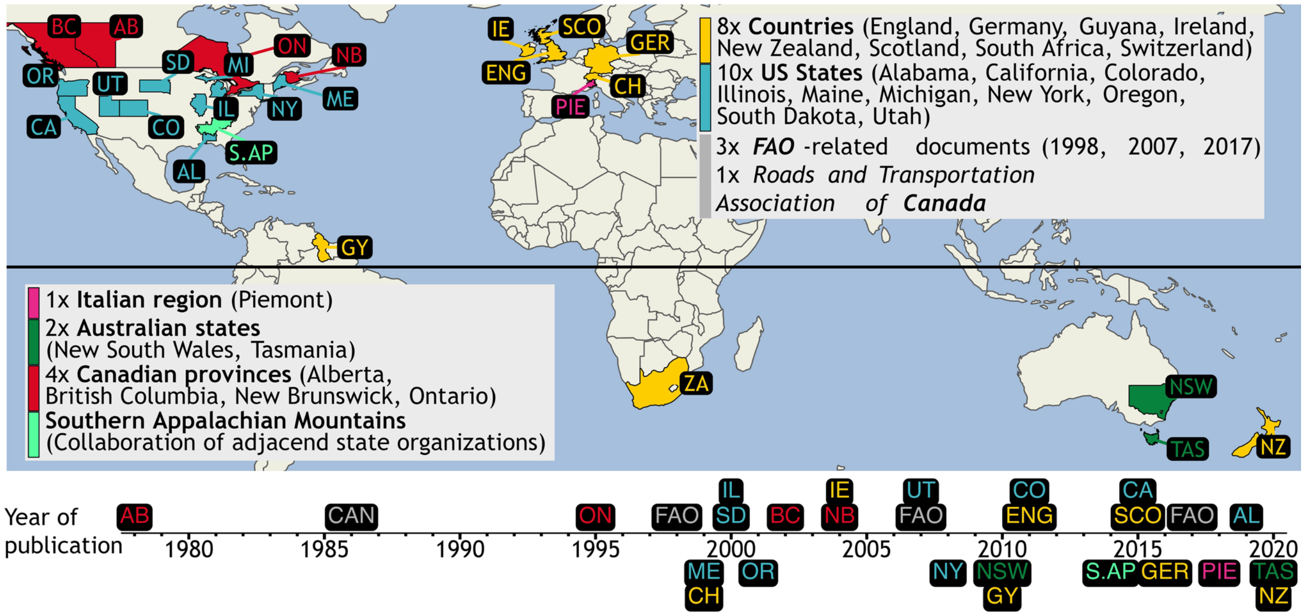

Fig. 3 Analyzed source documents: regions of origin and year of publication

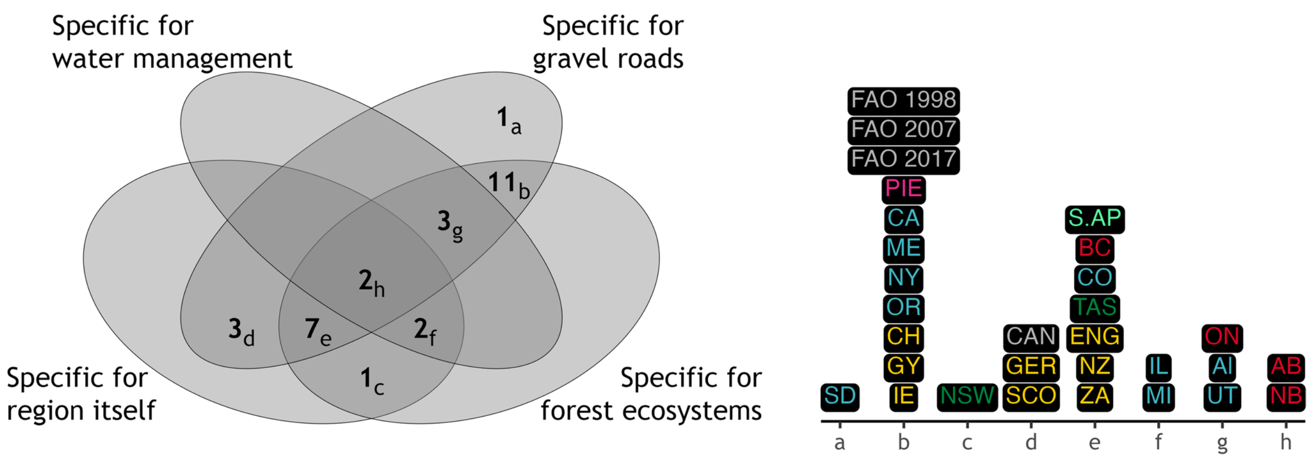

Fig. 4 Venn-diagram presenting the overlapping focus areas of the source documents specific to water management, gravel roads, forest ecosystems and the region of origin

use range (i.e., difference between minimum and maximum), this criterion could not be used for the categorical parameters. The latter was addressed by assessing these parameters with reference to the scientific literature. The number of sources with information was also considered as this could provide further insight into which design features were frequently addressed and thereby seemed to be most relevant.

Since significant design parameters of existing roads cannot be changed or can only be changed with enormous effort, it is also essential identifying those features that show potential for adaptation and thus have a reasonable chance of improving water management under climate change conditions.

Analyzed source documents

The systematic approach resulted in the identification of 32 relevant source documents. The geographical distribution of the regions of origin and publication years of these sources are depicted in Fig. 3. Their focus on either the region of origin, water management, gravel roads, or forest ecosystems are visualized in Fig. 4. A detailed list of the included documents is presented in Table 2.

The majority of the documents (28) originated from the Northern Hemisphere, while four came from the Southern Hemisphere. The documents covered 26 regions, with some regions delivering multiple sources. Two documents from

Table 2 Analyzed source documents from which forest road design parameters were identified

Case	Authors / publishing Institution	Title	Year
Alabama, US	Brinker, Richard W.; Tufts, Robert (Alabama Cooperative Extension System/Auburn University)	Forest Roads and Construction of Associated Water Diversion Devices, ANR-0916	2019
Alberta, CA	Rothwell, R.L.; Waldron, R.M.; Logan, P.A. (Northern Forest Research Centre, Edmonton)	Watershed management guidelines for logging and road construction in Alberta	1978
British Columbia, CA	B.C. Ministry of Forests, Victoria	Forest road engineering guidebook. Forest Practices Code of British Columbia Guidebook	2002
California, US	Weaver, W.E.; Weppner, E.M.; Hagans, D.K. (Mendocino County Resource Conservation District, Ukiah)	Handbook for Forest, Ranch and Rural Roads: A Guide for Planning, Designing, Constructing, Reconstructing, Upgrading, Maintaining and Closing Wildland Roads	2015
Canada	Roads and Transportation Association of Canada, Ottawa	2nd Edition of the Manual of Geometric Design Standards for Canadian Roads. Chapter H: Low-Volume Roads	1986
Colorado, US	Edwards, Richard M. (Colorado State Forest Service)	Colorado Forest Road Field Handbook	2011
England, UK	Forestry Commission, Bristol	Forest roads and tracks: Operations Note 25	2011
FAO	Winkler, Norbert	Environmentally sound road construction in mountainous terrain	1998
	Fannin, Jonathan R. (University of British Columbia, Vancouver); Lorbach, Joachim (Forest Products Service, Rome)	Guide to forest road engineering in mountainous terrain	2007
	Beguš, Jurij; Pertlik, Ewald	Guide for planning, construction and maintenance of forest roads	2017
Germany	DWA Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e. V., Hennef	Guidelines for access roads in rural areas [Richtlinien für den ländlichen Wegebau], German	2016
Guyana	Forestry Training Centre Inc., Georgetown	Manual on Introduction to Forest Roads and Considerations for Reduced Impact Logging	2010
Illinois, US	Bell, Keith; Carver, Andrew; Curtis, Stan; Murphy, Diane; Phelps, John; Stratton, Gary; Van Ormer, Dan, Brown, Stephanie; Conn, Wade; Kirkland, Jim; Newcomb, Joe; Schmoker, Dan; Throgmorton, Marland; Williams, Beecher (Illinois Department of Natural Resources, Illinois Forestry Development Council, Suthern Illinois University, University of Illinois)	Forestry Best Management Practices for Illinois	2000
Ireland	Ryan, Tom; Phililips, Henry; Ramsay, James; Dempsey, John (COFORD)	Forest Road Manual. Guidelines for the design, construction and management of forest roads	2004
Maine, US	Murphy, Allen; Connick, John (Seven Islands Land Company)	Forest Transportation Systems: Roads and Structures Manual	1999
Michigan, US	Snyder, Rick; Grether, Heidi; Creagh, Keith (Michig1an Department of Natural Resources, Lansing)	Michigan Forestry Best Management Practices for Soil and Water Quality	2018
New Brunswick, CA	Forest Management Branch, Natural Resources, Hugh John Flemming Forestry Centre, (Fredericton, New Brunswick)	Forest Management Manual for New Brunswick Crown Land Guidelines for roads and watercourse crossings	2004
New South Wales, AU	Department of Environment, Climate Change and Water NSW (Sydney South)	Private Native Forestry Field Guide for Northern NSW. Forest infrastructure	2010
New York, US	Swartz, Kurt C. (New York State Department of Environmental Conservation Bureau of State Land Management, Albany)	Unpaved Forest Road Handbook	2008
New Zealand	NZ Forest Owners Association (Wellington)	New Zealand Forest Road Engineering Manual	2020
Ontario, CA	Ministry of Natural Resources, Toronto	Environmental Guidelines for Access Roads and Water Crossings	1995
Oregon, US	Kramer, Brian W. (Oregon State University, Corvallis)	Forest Road Contracting, Construction, and Maintenance for Small Forest Woodland Owners	2001
Piemonte, IT	Bassani, Marco; Baglieri, Orazio; Catani, Lorenzo; Chiappinelli, Guiseppe; Tefa, Luca (Direzione Opere Pubbliche, Difesa del Suolo, Montagna, Foreste, Protezione Civile, Trasporti e Logistica Settore Foreste, Torino)	Guidelines for the design and construction of trails and roads in forestry [Linee guida per la progettazione e la costruzione di piste e strade in ambito forestale], Italian	2018

Table 2 (continued)

Case	Authors / publishing Institution	Title	Year
S. Appalachia, US	Alabama Forestry Commission; North Carolina Forest Service; Verginia Department of Forestry; Environmental Protection Agency of the United States; Natural Resources Conservation Service	A Guide for Forest Access Road Construction and Maintenance in the Southern Appalachian Mountains	2014
Scotland, UK	Scottish Natural Heritage, Inverness	Constructed tracks in the Scottish Uplands, 2nd Edition	2015
South Africa	Brink, Michal; Slate, Joel; Ackerman, Pierre; Cornell, Richard; de Wet, Pieter; Harrington, Phillip; Jones, Dave; Krieg, Benno; Lawrie, Dennis; Oberholzer, Francois; Timmerman, Mark; Shuttleworth, Brad (Institute for Commercial Forestry Research; Forestry Engineering South Africa)	South African Forest Road Handbook (FESA [date unknown])	n. d
South Dakota, US	Skorseth, Ken; Selim, Ali (South Dakota Local Transportation Assistance Program)	Gravel Roads: Maintenance and Design Manual	2000
Switzerland	Heinimann, Hans Rudolf; Bürgi, Othmar; Rechberger, Stefan (ETH): Bundesamt für Umwelt, Wald und Landschaft (BUWAL), Bern	Geometric standard values for forest roads and tracks [Geometrische Richtwerte von Waldwegen und Waldstrassen], German	1999
Tasmania, AU	Forest Practices Authority, Hobart	Forest Practices Code. Section B: Building Access to the Forest	2020
Utah, US	Daniels, Barbara; McAvoy, Darren; Kuhns, Mike; Gropp, Ron (Utah State University, Logan)	Managing Forests for Water Quality: "Stream Crossings" (009)	2004
		Managing Forests for Water Quality: "Forest Roads" (010)	2007

New Brunswick, NB, (Forest Management Branch 2004a, 2004b) and two from Utah, UT, (Utah State University 2004, 2007) were treated as one document per region. Some notable documents included those three published in relation to the Food and Agriculture Organization, FAO (1998, 2007, 2017), and a guide for forest access road construction and maintenance in the Southern Appalachian Mountains, published by several organizations in the bordering states (Alabama Forestry Commission et al. 2014). This guide is referred to as "S. Appalachia" or "S.AP" in figures.

Data analysis and presentation

All figures were created using open-source software *QGIS* (QGIS Development Team 2024) and *R version 4.4.2* (R Core Team 2024) within *RStudio version 2024.12.0+467* (Posit team 2024). Additionally, numerous packages were utilized to facilitate data analysis and visualization, including *cowplot* (Wilke 2023), *emmeans* (Lenth 2023), *ggrepel* (Slowikowski 2024), *ggtext* (Wilke and Wiernik 2022), *ggthemes* (Arnold 2024), *glue* (Hester and Bryan 2024), *patchwork* (Pedersen 2024), *RColorBrewer* (Neuwirth 2022), *sf* (Pebesma 2018), *terra* (Hijmans 2023), and functions from *tidyverse* (Wickham et al. 2019). The map in Fig. 3 was made possible due to the geometry shapefiles provided by the Istituto Nazionale di Statistica 2016 and the *R* packages *canadianmaps* (Cayen 2023), *ozmaps* (Sumner 2023), *spData* (Bivand et al. 2024), and *usmaps* (Di Lorenzo 2023).

Results

Overview

Table 3 shows the results of the analysis for all the source documents and parameters. Figures 5 and 6 present comparisons for the quantitative and categorical forest road design parameters, respectively.

Alignment

Three specifications for the vertical alignment (lower, upper, and extreme limit) were generally included in the source documents. In particular, the upper limit of the road gradient was specified in all but four sources. This was different for the horizontal alignment, where 17 of the sources did not provide information. There was consensus in the sources on the upper limit of the road gradient, with a mean of approx. 11% (Coefficient of Variation $[CV]=0.21$). This clarity appears to be lacking for the lower limit, where values from 0 to 3% were given (Mean $[M]=1.8\%$, $CV=0.56$).

Cross-sectional profile

Little information was provided for road and crown width. However, attention should be paid to the limits of cross-sectional slope. The absolute lower limit of 2% and the maximal cross-sectional slope of 12% differ widely. However, most of the values were in the range of 3 to 6%, as indicated by the small *CV*s for both features, namely 0.31 for the lower limit and 0.36 for the upper limit. Although no type of profile was specifically excluded as a possibility, about half of the sampled source document did not provide any cross-sectional profile recommendation.

Side slopes

Most of the sources included a table for cut and fill slopes to meet the local requirements. Here, only the absolute maximum values given in each of the sources were considered. These values differed visibly from one another: the cut slope may be steeper than the fill slope, reflected by a mean of 185.2% (CV = 0.75) compared to 106.6% (CV = 0.97). Only ten of the sources provided information on how to proceed if the stability of cut- or fill-slopes is insufficient. The most frequently mentioned options were ripraps (i.e., large rocks; n = 10), geotextiles and vegetation (n = 9). The drainage of slopes was advised in six sources. The least popular options were fascines (n = 1) and berms (n = 3).

Ditches

Recommended types

While the majority did not include any specification on the types of ditches, those that did preferred mainly the "V"-shaped ditch (n = 12), due to ease of maintenance. A ditch in the form of a trapezoid was the second most recommended ditch type (n = 7). Four sources included advice for the use of large rocks (riprap) or geotextiles for armoring the ditch in cases of severe erosion risk (Colorado State Forest Service 2011; Mendocino CRCD 2015; Directorate of Forestry Piemonte 2018; NZ Forest Owners Association 2020).

The "U"-shaped ditch is an example of the diversity and controversy of road design features covered in the analyzed source documents. A total of 24 sources did not include any specification on this, two recommended it, while four discouraged its use due to maintenance limitations and instability of the ditch sides. The latter included British Columbia (B.C. Ministry of Forests 2002), England (Forestry Commission 2011), New Brunswick (Forest Management Branch 2004b), and South Africa (FESA [date unknown]). Sources that mentioned the "U"-shape as a recognized alternative, were the Germany guideline and the handbook for Piemonte, Italy (DWA 2016; Directorate of Forestry Piemonte 2018).

Alignment and dimension

Only a few sources included information for practitioners on the design of ditches in terms of width (n = 7, M = 0.6 m), depth (n = 8, M = 0.3 m), or the cross-sectional slope of the ditch edge (n = 4, M = 75%). Values for the vertical gradient of ditches ranged from 0.5% (n = 10, M = 1.1%) to 8.0% (n = 4, M = 6%), which corresponded to the lower end of the observed values for the vertical gradient of the road itself. It does not seem to be considered a problem that ditches can be oversized, as a total of three figures were found for the corresponding parameters, namely the upper limits for width (n = 2, M = 0.95 m) and depth (0.6 m).

Ditch relief structures

Culverts as ditch relief structure: dimension and installation

Culverts are among the most important ditch relief structures. Consequently, two-thirds of the sources included information on their dimensional specifications (n = 20, M = 376.4 mm). However, less instruction was found on their installation. While consensus on the limits on the orientation of the culvert relative to the road axis was found, with a mean of 25.9° (CV = 0.29) and 39.4° (CV = 0.20), the lower (M = 2.3%; CV = 0.52) and upper limits (M = 6.4%; CV = 0.95) for the slope of the culvert seemed to be more controversial considering the higher *CV* values.

Spacing

Opposing views were found regarding the spacing of ditch relief structures. Firstly, more than half of the sources were in favor of determining the maximum spacing in relation to the vertical gradient of the road (n = 17). Four sources provided a corresponding formula to determine the required frequency (compare Fig. 7). These included the manuals of Alabama (Alabama Cooperative Extension System and Auburn University 2019), Alberta (Northern Forest Research Centre 1978), New Brunswick (Forest Management Branch 2004b), and Ireland (COFORD 2004). The second group was not in favor of deciding optimal spacing based solely on a single calculatable factor. The guideline from California should be cited here as an example, where the necessary spacing "[…] is not a one-size-fits-all approach and requires the evaluation of site-specific conditions" (Mendocino CRCD 2015). Examples of these local site conditions are quoted from WDNR 2011, including vertical alignment, precipitation, soil type, and location of other drainage structures.

Maine's manual also belongs to the second group, according to which the corresponding structures should be implemented pragmatically "[…] as often as necessary […]"

Table 3 Condensed results for all design parameters and source documents

		Alabama, US	Alberta, CA	British Columbia, CA	California, US	Canada	Colorado, US	England, UK	1998 FAO	FAO 1998, 2007, 2017	2017	Germany	Guyana	Illinois, US	Ireland	Maine, US	Michigan, US	New Brunswick, CA	New South Wales, AU
Alignment																			
Road gradient [%]	Lower limit	2.0	3.0		3.0		2.0	3.0	2.0	2.0			2.0	1.0	1.0		2.0		
	Upper limit	13.0	10.0	12.0	12.0	11.0	10.0	7.0	16.0	10.0		8.0	12.0	10.0	10.0		10.0		17.6
	Extreme (for short distances)		20.0	14.0	20.0	16.0	12.0	18.0		14.0		12.0	20.0				20.0		26.8
Narrowest horizontal curve [m]				35.0	24.4	30.0	15.2	10.0				12.0	20.0		20.0				
Design speed [km h^{-1}]			30.0	88.5	30.0		25.0		30.0		30.0	32.0							40.2
Cross-sectional profile																			
Recommendation for profile	crowned		✓		✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓				✓
	insloped		✓		✓	✓	✓		✓	✓	✓	✓	✓	✓					✓
	outsloped		✓		✓	✓	✓			✓		✓	✓	✓					✓
Cross-sectional slope [%]	Lower limit				3.0	2.0	2.0	4.5	2.0	4.0		3.0	4.0	2.0	4.0		4.0		4.0
	Upper limit		4.0		5.0	4.0	4.0	8.0	6.0	12.0		6.0	8.0	4.0	7.0		6.0		6.0
Crown width [m]	Lower limit							5.4		5.0		4.5	9.0		4.0			5.5	
	Upper limit							6.0		6.0		5.0							
Road width [m]	Lower limit				4.9		7.3	3.2				3.5	6.0		3.0		3.7		
	Upper limit				6.1		9.1					3.5							
Side slopes																			
Stabilization	with berms															✓			
	with compaction									✓									✓
	with drainage							✓					✓						✓
	with fascine									✓									
	with gabion									✓									
	with geotextiles				✓					✓			✓			✓			
	with riprap				✓		✓			✓			✓	✓		✓			
	with vegetation		✓				✓			✓				✓					✓
	Examples									✓			✓	✓		✓			
Cut slope [%]	Upper limit		400	400	400	67	400	100		133	200	100	100	67	67			50	
Fill slope [%]			100	100	400	67	400	50		100	150	67	50	33	67			50	

Table 3 (continued)

		Alabama, US	Alberta, CA	British Columbia, CA	California, US	Canada	Colorado, US	England, UK	1998 FAO	FAO 1998, 2007, 2017	2017	Germany	Guyana	Illinois, US	Ireland	Maine, US	Michigan, US	New Brunswick, CA	New South Wales, AU
Ditches																			
Recommended ditch type	"U"			×				×				✓						×	
	"V"			✓	✓	✓		✓		✓	✓	✓	✓					✓	
	"armored"				✓		✓												
	"trapezoid"			✓		✓		✓				✓							
Depth [m]	Lower limit		0.5		0.3			0.2				0.2	0.3					0.3	
	Upper limit																		
Width [m]	Lower limit		0.9		0.6							0.3						0.3	
	Upper limit				0.9							1.0							
Vertical gradient [%]	Lower limit		0.5	2.0				2.0	2.0	2.0	2.0		1.0						
	Upper limit							6.0	8.0				5.0						
Cross-slope [%]	Upper limit																	50	
Ditch relief structures																			
Spacing																			
Consideration of factor	Alignment	✓	✓	✓	✓			✓		✓			✓	✓	✓			✓	✓
	Culvert dimension																		
	Erosion		✓	✓	✓					✓					✓			✓	
	Local knowledge			✓	✓					✓									
	Maintenance																		
	Precipitation		✓	✓	✓			✓							✓				
	Upstream area			✓															
Distance [m]	Lower limit	24			15		200	25		15			30	34	20		11		40
	Upper limit	91			91		900	200		150			80	152	80		76		150
Culverts																			
Lower limit for diameter [mm]	457		400	457		457	300		300		400	450	305	375	305	305	300		
Slope [%]	Lower limit	2.0	3.0	1.0	2.0		3.0			2.0			1.0	2.0		2.0	2.0	4.0	
	Upper limit	4.0	20.0	2.5				5.0		6.0			3.0			4.0			
Rotation [°]	Lower limit	30		30			30							30			30	30	
	Upper limit			45	30									45		30	45		

Table 3 (continued)

		Alabama, US	Alberta, CA	British Columbia, CA	California, US	Canada	Colorado, US	England, UK	1998 FAO	FAO 1998, 2007, 2017	2017	Germany	Guyana	Illinois, US	Ireland	Maine, US	Michigan, US	New Brunswick, CA	New South Wales, AU
Ditch relief into/ near to stream	Acceptable	×	×		×		×	×				✓	×	×	×	×	×	×	×
	Min. Spacing [m]				15.2		15.2						50.0		25.0		15.0	30.0	5.0
Mitre drains / off-take-ditches	Recommendation	✓			✓								✓	✓		✓	✓	✓	✓
	Width [m]																		
Structures for outlet armoring		✓	✓		✓			✓		✓			✓	✓					✓
Inventory of ditch relief structures			✓													✓	✓		
Stream crossings																			
Crossings with fords			✓	✓	✓		✓	×		✓	✓		✓	✓	✓			✓	✓
Hydraulic calculation																			
Suggested formula	Any		✓		✓			✓						✓	✓				
	Rational formula							✓							✓				
	Talbot formula		✓		✓														
Return periods for peak flows [a]			100	100		25			25					25		100	100	10	
Consideration of climate change							✓												
Examples for stream crossings		✓	✓	✓		✓	✓		✓				✓	✓		✓	✓	✓	
Culverts																			
Lower limit for diameter [mm]				600				300			400		450	305				450	
Slope [%]	Lower limit		3.0										1.0					0	
	Upper limit		20.0							2.0			3.0					0.5	
n		12	28	25	39	12	27	33	9	34	9	23	35	26	23	11	17	23	21
		New York, US	New Zealand	Ontario, CA	Oregon, US	Piemonte, IT	S. Appalachia, US	Scotland, UK	South Africa	South Dakota, US	Switzerland	Tasmania, AU	Utah, US	Overall					n
Alignment																			

Table 3 (continued)

		New York, US	New Zealand	Ontario, CA	Oregon, US	Pie-monte, IT	S. Appa-lachia, US	Scotland, UK	South Africa	South Dakota, US	Switzer-land	Tasma-nia, AU	Utah, US	Overall					n
Road gradient [%]	Lower limit		0	1.0	2.0	3.0	0	2.5	0		2.0			*M* (sd):		1.8		(1.0)	19
	Upper limit	10.0	12.0	10.0	12.0	14.0	10.0	10.0	9.0		12.0	12.0	10.0	*M* (sd):		11.1		(2.3)	26
	Extreme (for short dis-tances)	15.0	18.0		20.0	18.0	15.0	12.5	20.0		15.0	15.0		*M* (sd):		17.1		(3.7)	20
Narrowest horizontal curve [m]		15.2	18.0				10.7	10.0	35.0					*M* (sd):		19.7		(9.0)	13
Design speed [km h^{-1}]		30.0						30.0		40.0				*M* (sd):		36.9		(17.7)	11
Cross-sectional profile																			
Recom-menda-tion for profile	crowned	✓	✓		✓		✓		✓	✓				×:	0%		✓:	64%	19
	insloped				✓	✓	✓		✓					×:	0%		✓:	50%	15
	outsloped				✓	✓	✓		✓					×:	0%		✓:	43%	13
Cross-sec-tional slope [%]	Lower limit		4.0		2.0	2.0			4.0	4.0				*M* (sd):		3.2		(1.0)	17
	Upper limit		6.0		4.0	4.0			6.0					*M* (sd):		5.9		(2.1)	17
Crown width [m]	Lower limit	4.3							6.0					*M* (sd):		5.5		(1.6)	8
	Upper limit								7.0					*M* (sd):		6.0		(0.8)	4
Road width [m]	Lower limit	3.7	4.0		4.0	4.0	4.3	3.0			3.0			*M* (sd):		4.1		(1.2)	14
	Upper limit						6.0							*M* (sd):		6.2		(2.3)	4
Side slopes																			

Table 3 (continued)

		New York, US	New Zealand	Ontario, CA	Oregon, US	Pie-monte, IT	S. Appa-lachia, US	Scotland, UK	South Africa	South Dakota, US	Switzer-land	Tasma-nia, AU	Utah, US	Overall					n
Stabiliza-tion	with berms		✓	✓										×:	0%		✓:	10%	3
	with com-paction		✓	✓										×:	0%		✓:	13%	4
	with drain-age		✓			✓			✓					×:	0%		✓:	20%	6
	with fascine													×:	0%		✓:	3%	1
	with gabion		✓	✓		✓			✓					×:	0%		✓:	17%	5
	with geo-textiles		✓	✓		✓			✓			✓		×:	0%		✓:	30%	9
	with riprap	✓		✓		✓						✓		×:	0%		✓:	33%	10
	with veg-etation		✓	✓		✓						✓		×:	0%		✓:	30%	9
	Examples	✓	✓	✓		✓			✓			✓		×:	0%		✓:	33%	10
Cut slope [%]	Upper limit	100	400		200		67	67	200					*M* (sd):		185.2		(139.7)	19
Fill slope [%]		100	80	67	67		50	67	67					*M* (sd):		106.6		(103.7)	20
Ditches																			
Recom-mended ditch type	"U"					✓			×					×:	13%		✓:	7%	6
	"V"		✓		✓				✓					×:	0%		✓:	40%	12
	"armored"		✓			✓								×:	0%		✓:	13%	4
	"trap-ezoid"		✓			✓			✓					×:	0%		✓:	23%	
Depth [m]	Lower limit		0.3		0.3									*M* (sd):		0.3		(0.1)	8
	Upper limit		0.6																1
Width [m]	Lower limit				0.9	0.5	0.6							*M* (sd):		0.6		(0.3)	7
	Upper limit																		2
Vertical gradient [%]	Lower limit		0.5		2.0				0.5					*M* (sd):		1.1		(0.7)	10
	Upper limit								5.0					*M* (sd):		6.0		(1.4)	4
Cross-slope [%]	Upper limit		50		50				150					*M* (sd):		75.0		(50.0)	4
Ditch relief structures																			

Table 3 (continued)

		New York, US	New Zealand	Ontario, CA	Oregon, US	Pie-monte, IT	S. Appa-lachia, US	Scotland, UK	South Africa	South Dakota, US	Switzer-land	Tasma-nia, AU	Utah, US	Overall					n
Spacing																			
Consider-ation of factor	Alignment		✓	✓	✓	✓			✓			✓		×:	0%		✓:	57%	17
	Culvert dimen-sion		✓		✓				✓					×:	0%		✓:	10%	3
	Erosion		✓	✓	✓				✓			✓		×:	0%		✓:	37%	11
	Local knowl-edge				✓	✓			✓			✓		×:	0%		✓:	23%	7
	Mainte-nance								✓					×:	0%		✓:	3%	1
	Precipita-tion				✓	✓			✓			✓		×:	0%		✓:	30%	9
	Upstream area								✓					×:	0%		✓:	7%	2
Distance [m]	Lower limit		40	100	61	100	46		75			30		*M* (sd):		50.9		(47.2)	17
	Upper limit		350	600	244	150	61		750			150		*M* (sd):		251.5		(253.9)	17
Culverts																			
Lower limit for diam-eter [mm]		457	325	500	305		381		450			300		*M* (sd):		376.4		(72.5)	20
Slope [%]	Lower limit		3.0		2.0	5.0			0.0					*M* (sd):		2.3		(1.2)	15
	Upper limit													*M* (sd):		6.4		(6.1)	7
Rotation [°]	Lower limit	10	20		30				30				15	*M* (sd):		25.9		(7.4)	11
	Upper limit				45				45				30	*M* (sd):		39.4		(7.8)	8
Ditch relief into/near to stream	Acceptable		×	×			×		✓			×	×	×:	60%		✓:	7%	19
	Min. Spac-ing [m]								50.0			50.0		*M* (sd):		28.4		(17.6)	9
Mitre drains / off-take-ditches	Recom-menda-tion		✓	✓			✓		✓			✓	✓	×:	0%		✓:	47%	14
	Width [m]								1.0										1
Structures for outlet armoring			✓				✓	✓	✓				✓	×:	0%		✓:	43%	13
Inventory of ditch relief structures			✓											×:	0%		✓:	13%	4

Table 3 (continued)

		New York, US	New Zealand	Ontario, CA	Oregon, US	Pie-monte, IT	S. Appa-lachia, US	Scotland, UK	South Africa	South Dakota, US	Switzer-land	Tasma-nia, AU	Utah, US	Overall					n
Stream crossings																			
Crossings with fords			✓				✓		✓			✓	✓	×:	3%		✓:	53%	17
Hydraulic calculation																			
Suggested formula	Any		✓				✓		✓			✓		×:	0%		✓:	30%	9
	Rational formula						✓		✓					×:	0%		✓:	13%	4
	Talbot formula		✓									✓		×:	0%		✓:	13%	4
Return periods for peak flows [a]			50		50			200	50			50	50	*M* (sd):		66.8		(49.6)	14
Consideration of climate change			✓					✓						×:	0%		✓:	10%	3
Examples for stream crossings		✓	✓		✓		✓	✓	✓			✓	✓	×:	0%		✓:	63%	19
Culverts																			
Lower limit for diameter [mm]		457	450	500		600	457						381	*M* (sd):		445.9		(94.5)	12
Slope [%]	Lower limit					5.0		1.0	1.0			0.9		*M* (sd):		1.7		(1.7)	7
	Upper limit								3.0			3.5		*M* (sd):		5.3		(7.3)	6
n		15	40	18	19	26	23	13	48	3	4	23	10						

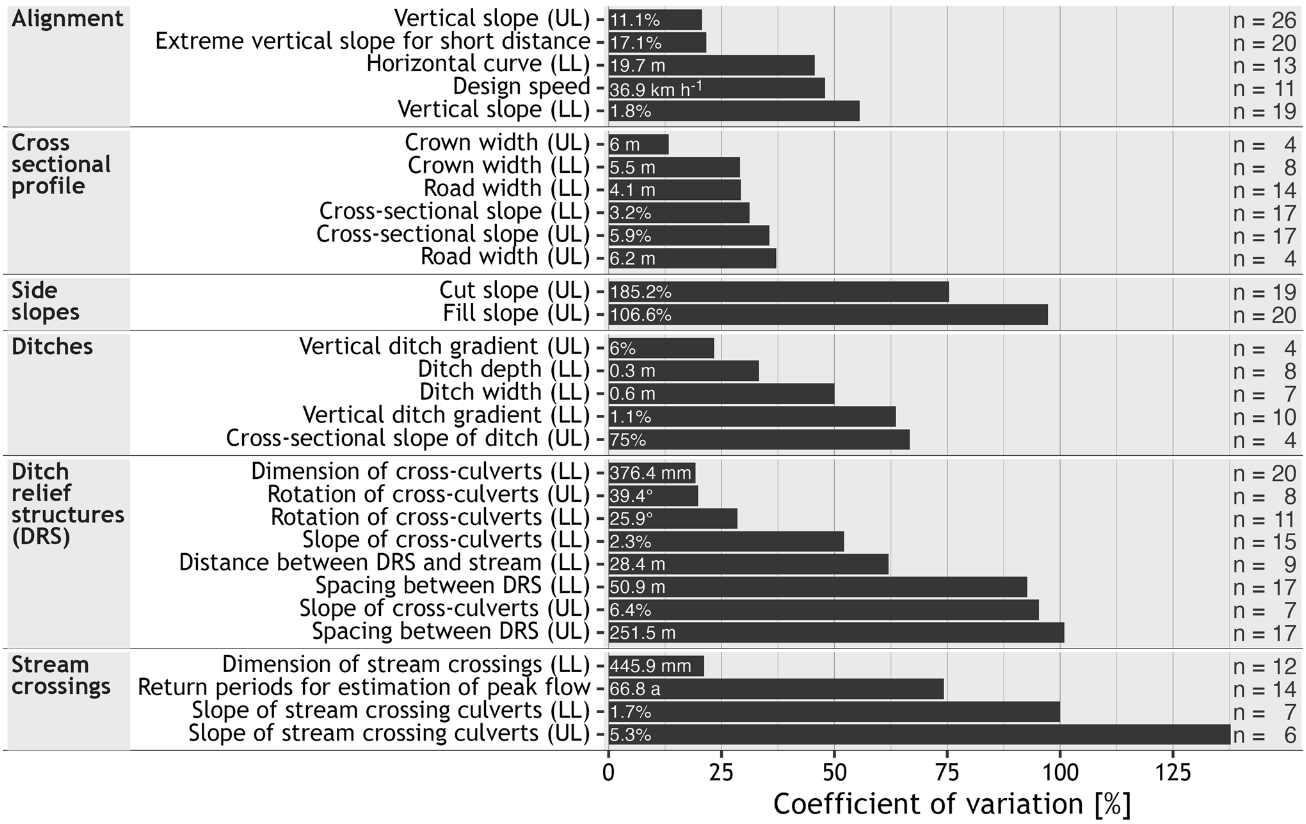

Fig. 5 Coefficient of variation (CV) in percent and means of the quantitative design features. DRS = Ditch relief structures, LL = Lower limit, UL = Upper limit. For detailed values please refer to Table 3

(Seven Islands Land Company 1999). The third group of guidelines that mentioned spacing contains tables which, based on various factors, specify distances between the ditch relief structures, e.g., the manuals from Colorado (Colorado State Forest Service 2011) or Tasmania (Forest Practices Authority, Tasmania 2020). Here too though, an opposing view was found, for example in the guidebook from British Columbia: "[…] With so many factors influencing placement of cross-drain culverts, it is not recommended that spacing tables be used unless the designer has experience and augments the tables with consideration of site-specific conditions" (B.C. Ministry of Forests 2002). Similar to the list from Mendocino CRCD (2015), the factors precipitation, soil type, and elevation are used to determine necessary spacing (B.C. Ministry of Forests 2002).

However, since most of the sources included advice about spacing with consideration of vertical alignment, Fig. 7 shows the upper and lower limit of spacing and the advised range of vertical gradient. Dashed segments connect lower limits and upper limits for representing the range (A). In addition, the results for the four formulae are plotted against the vertical gradient on the right side of the plot (B). Overall, full recommendations (lower and upper limits for both vertical alignment and ditch relief structure spacing or a spacing formula) were found in 19 source documents.

Ditch relief into stream

Only two guidelines (South Africa and Germany) found the discharge of ditch water into streams under certain conditions acceptable (FESA [date unknown]; DWA 2016). Overall, though, consensus was found ($n = 17$) in separating ditches from streams and other water bodies by releasing run-off water into riparian buffer zones. Nine of the sources included a lower limit for the distance between ditch relief structures and streams. Furthermore, although discharge into streams is possible, the South African guideline advises a minimum distance from the outlet of the ditch relief to the stream of 50 m. All data resulted in a mean of 28.4 m ($CV = 0.62$) and a median of 25 m.

Further information on ditch relief structures

For the reduction of erosion at the outlet of culverts, various structures are advised in 13 source documents. Coarse stones placed at the outlet are usually used as dissipater structures, however other materials such as cut-up plastic or

			No	Not specified	Yes
Cross-sectional profile	Recommended profile	Outsloped		17	13
		Insloped		15	15
		Crowned		11	19
Side slopes: Stabilization		With fascine		29	1
		With berms		27	3
		With compaction		26	4
		With gabione		25	5
		With drainage		24	6
		With vegetation		21	9
		With geotextiles		21	9
		With riprap		20	10
		Examples for design		20	10
Ditch	Recommended Ditch type	"U"	4	24	2
		"armored"		26	4
		"trapezoid"		23	7
		"V"		18	12
Ditch relief	Spacing of ditch relief structures (DRS) based on	Maintenance		29	1
		Upstream area		28	2
		Culvert dimension		27	3
		Local knowledge		23	7
		Precipitation		22	8
		Erosion		19	11
		Alignment		13	17
	Further Information	Discharge directly into stream	17	11	2
		Inventory of DRS		28	2
		Culvert outlet protection		17	13
		Mitre drains / off-take-ditches		16	14
Stream crossings	Hydraulic calculations	Consideration of climate change		27	3
		Talbot formula		26	4
		Rational formula		26	4
		Recommendation of any formula		23	7
		Examples for design		11	19
	Fords	Recommendation	1	13	16

Fig. 6 Categorical design features—Number of specific recommendations in the sampled source documents

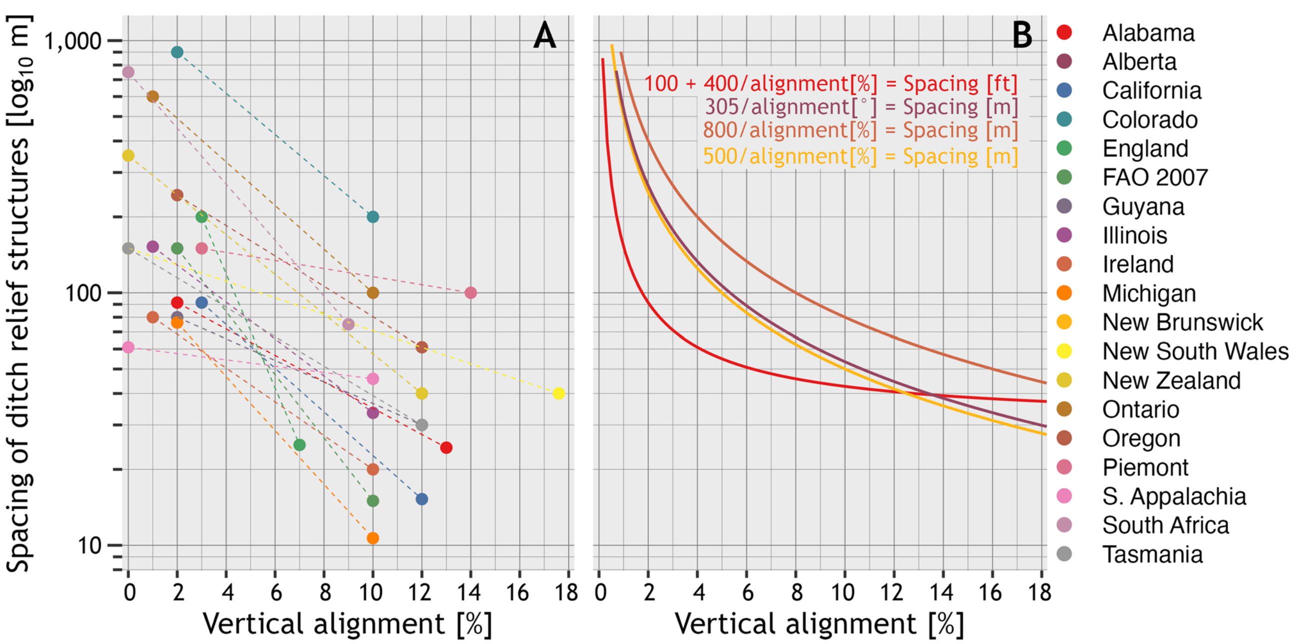

Fig. 7 Recommended spacing of ditch relief structures according to different source documents. Panel A shows the minimum and maximum values for spacing, and vertical alignment, respectively. Panel B visualizes the four formulae that can be used to calculate the required frequency of spacing as function of vertical alignment, found in source documents from Alabama, Alberta, Ireland, and New Brunswick

metal culverts made from galvanized iron are also suggested (Colorado State Forest Service 2011; NZ Forest Owners Association 2020).

Nearly half of the sources (n = 14) recommended the implementation of mitre drains, also known as off-take-ditches, diversion ditches, wing ditches, lead-out ditches, or turnouts. These terms refer to lateral branches off the main ditch direction, so that water from the ditch is regularly drained into adjacent forest stands. Some of these structures are also used to ensure that water from the ditches does not end up in the streams (see "Ditch relief into Stream" above).

Two sources recommended marking of ditch relief locations—The older Guideline from New Brunswick proposed flagging of inlets, while the newer Handbook for New Zealand advised recording positions of ditch relief culverts using GNSS (Forest Management Branch 2004a; NZ Forest Owners Association 2020).

Water crossings

Use of fords for stream crossings

Half of all sources covered the use of fords for stream crossings (n = 16). The only source that opposed fords stemmed from England, in which the practice is explicitly not recommended, arguing that fords can be a source of pollution and a cause for hydrodynamic scour downstream (Forestry Commission 2011).

Return periods for estimated peak flow and consideration of climate change

Using return periods to estimate peak flow was recommended in 14 source documents, equaling a median of 50 years ($M = 66.8$, $CV = 0.74$). The sources from England (Forestry Commission 2011), Scotland (Scottish Natural Heritage 2015), and from New Zealand (NZ Forest Owners Association 2020) propose dimensioning of stream crossings according to climate change conditions, meaning dimensioning crossings towards expected increased peak flows. New Zealand's handbook listed a return period length of 50 years, while the English and Scottish sources did not include any information on return period length.

Design of stream crossings

Stream crossings were covered by two thirds (n = 19) of the source documents. These documents contain examples for the design of stream crossings in terms of calculating the necessary cross-sectional area, which translates to the minimum diameter (n = 12) when using culverts. Straightforward approaches are explained in the sources, whereby either the bankfull width or a high-water mark is determined by field observations and multiplied by a safety factor, e.g., the "*MESBOAC*"-method from Michigan's handbook (Michigan DNR 2018), the British Columbian "high water estimation"-method for stream culverts smaller than 2,000 mm (B.C. Ministry of Forests 2002), or the *Hasty* method after Darrach et al. (1981), which is cited in the 2011 published handbook for Colorado (Colorado State Forest Service 2011). Furthermore, information on formulae that can be used to calculate the necessary diameters can be found (n = 7). These are usually based on size and land-use of the catchment area, for example the *Rational* method (n = 4) or the *Talbot* formula (n = 4).

Besides information on minimum culvert diameter, instructions for the lower (n = 7, $M = 1.7\%$, $CV = 1.0$) and upper gradient limit (n = 6, $M = 5.3\%$, $CV = 1.38$) of culverts were found. However, the given numbers varied considerably, indicated by high *CV*s. While some sources suggested shallower gradients, e.g., New Brunswick, and Guyana, the older handbook from Alberta (1978) suggested steeper gradients (up to 20%). Still, the authors agree that the natural streambed should remain undisturbed as far as possible. This can be achieved by aligning the crossing with the natural course of the streambed, which allows for accumulation of sediment on the base of the culvert mimicking a natural streambed and reducing potentially damaging barrier effects. The guideline from Michigan should be mentioned here as an example, where a deviating gradient is cited as the main reason for preventing fish passage (Michigan DNR 2018).

Discussion

Parameters and source documents

It is hardly possible to describe complex systems such as forest roads using only design parameters. While the list presented in this article is extensive, it is not considered complete. For example, aspects with influence on water balance and drainage, such as mulching (Solgi et al. 2021) or the restoration (Luce 1997) of forest roads were not included since the focus of the analysis was on design features, rather than on road maintenance or decommissioning.

Nevertheless, it is assumed that due to the broad selection of source documents in legislation, guidelines, and handbooks, and the frequently recurring principles therein, a large proportion of the relevant drainage and water management design parameters were considered in this review. It should be noted that water management and drainage are not the predominant aspects of forest road engineering and thus of the source documents analyzed (Fig. 4). Still, these parameters are highly relevant and under climate change conditions, probably of increasing importance.

Mainly freely accessible, open-access source documents were used in this review. Due to their availability in the library of the *Department of Forest Work Science and Engineering*, only two other non-publicly available source documents (Germany, and Maine) were included in this review, which may have limited the analysis to some extent. Nevertheless, 32 documents from 26 regions were included in this study. In view of the broad variety of climatic conditions prevalent in the analyzed regions (Fig. 3), we assume that the analysis allows for in-depth insight into how drainage of forest roads and water management along them is realized worldwide.

Practical implementation of the source documents

From the analysis it is clear that decisions on some of the design parameters are left to those who design, build, and maintain the road. For example, some of the documents advise for the spacing of ditch relief structures and cross-slope of ditches to be based on local knowledge. Only half of the sampled documents (n = 15) declared specificity to the region it was written for (Fig. 4). This makes it difficult to assess whether the design parameters are implemented in their defined form. Especially since, at the time of writing this review, some of the documents are already several decades old (e.g., Alberta`s guidelines were published in 1978) and may no longer be applicable on a one-to-one basis.

It is also conceivable that local interpretations and best practices of the official guidelines exist. For instance, we are aware that several specific guidelines at federal state level exist in Germany. Similar constellations could also prevail in other regions of the world. The median area coverage of the regions considered in this review was 20.47 million hectares. The smaller the area a guideline document is intended for, the more unique the differences to other regions could be. This theory can be supported by the fact that, for example, only relatively few design parameters are defined in the three guidelines linked to the FAO, presumably because they are intended to be applicable to all regions of the world.

Qualitative design parameters

The examination of qualitative design parameters should also by no mean be considered an exhaustive list. Nevertheless, these parameters are important, since they allow for holistic communication of forest road design-quality parameters that are otherwise not defined using definitive numbers.

Most of the documents analyzed focused on water drainage. One example here can be taken from the South Dakota Manual for Gravel Roads, which quotes that the "[…] three most important things to understand in building and maintaining roads are drainage, drainage and drainage" (South Dakota LTAP 2000). However, the documents are not only aimed at the drainage of water. The North American guidelines, for example, include a list of best management practices or at least make regular reference to such documents. For example, the California manual provides numerous examples of how to avoid hydrologic connections between road ditches and streams. These include locating roads away from streams, not allowing ditch relief into streams, and recommending side drains (Mendocino CRCD 2015). Interestingly, however, draining, and thus the loss of water from the forest ecosystem through road ditches into streams (Toman 2004) is not considered in this context. Instead, focus is shifted to limiting sediment intake by road runoff.

Sedimentation seems to be one of the main topics/concerns in the documents analyzed, alongside drainage and thus securing trafficability of the roads. For example, documents from Ontario and New Zealand present measurements for erosion control such as implementation of check dams, sediment traps, brush barriers, silt fences or diversion berms using illustrations (Ministry of Natural Resources 1995; NZ Forest Owners Association 2020). This is unsurprising in view of the relevant literature (Kraebel 1936; Reid and Dunne 1984; Croke et al. 2005; Jordán-López et al. 2009). Overall, little content in the analyzed documents was concerned with adapting road structures to new climate change related challenges such as heavy precipitation events. However, one example of such adaptation includes an illustration of diversion ditches in the Illinois and Michigan guidelines (Illinois DNR 2000; Michigan DNR 2018).

Typical practices and potential for climate change adaptation

Alignment

Road design highly depends on design speed (Donnell et al. 2009; AASHTO 2018), which in the documents analyzed is on average 36.9 km h^{-1} (*median*: 30 km h^{-1}). This is particularly relevant for the narrowest curve radii, which, being at least 20 m, is suitable for longer vehicles such as timber trucks. Lower design speeds enable the construction of landscape-adapted roads, thereby reducing the impact on the ecosystem and hillsides (AASHTO 2018). Additionally, slower speeds help to minimize dust emissions from unpaved gravel materials (Gillies et al. 2005; Jia et al. 2013), which can lead to further erosion of the road surface through changing particle-size distributions (Frankel and Tahmoorian 2023). This can have severe impacts on human health and adjacent ecosystems (Jones 1999; Edvardsson and Magnusson 2009).

We therefore argue, that raising low design speeds, such as we found in the guidelines analyzed, and horizontal alignment to climate change conditions should not be considered, especially in view of potentially prolonged droughts (Dai et al. 2018; Kupec et al. 2021), that could create more frequent dry conditions that accelerate dust erosion (South Dakota LTAP 2000). In addition, to avoid road damage, operating speed should be lowered during droughts.

The vertical alignment of roads is designed to ensure safe passage of timber trucks, while considering the increased erosivity of water on steeper vertical gradients (Cao et al. 2014; Varol et al. 2019; Valencia-Gallego and Montoya 2024). Our analysis showed an average upper limit for road gradient of 11.1%, with extreme limits of up to 26% ($M = 17.8\%$) and lower limits averaging 1.9%. We argue that, especially under conditions of climate change, the implementation of a lower limit is essential in regions with hilly or mountainous terrain. While implementing a lower limit in vertical alignment may be challenging for practitioners in flatter regions, it is essential for drainage in regions with complex terrain. In any case, if the vertical alignment is too low, the slope of the cross-sectional profile (i.e., superelevation) becomes more important (Lienert 1983).

However, since the construction of new forest roads constitutes only a small share of the total already in existence, the potential of adapting vertical and horizontal alignment to address climate change is relatively low. Yet, it should be noted that the vertical alignment is an important indicator of potential damage to the road by water erosion (Lienert 1983). More frequent and heavier precipitation events in a changing climate can cause severe damage to drainage systems and the road itself with increasing risk in steep terrain (Cao et al. 2014; Varol et al. 2019; Valencia-Gallego and Montoya 2024).

Cross-sectional profile

Most of the analyzed documents were in favor of a crowned cross-sectional profile (n = 19) with a cross-sectional slope of 3.2% ($CV = 0.31$) to 5.9% ($CV = 0.36$). Road widths should be minimized to reduce the impact of water runoff and thus the forest ecosystem (e.g., reduced infiltration rate on the road, see Fig. 1). However, roads should still be wide enough for safe passage of logging trucks and road width is also dependent on design speed (Donnell et al. 2009). Both of these points could explain why the upper and lower limits of road dimensions do not show a significant range. All in all, the potential for adaptation to climate change is low for most design features related to the cross-sectional profile. However, the superelevation of cross-sectional slopes can be adapted even on existing roads, which is especially necessary in flatter regions in order to improve drainage (Lienert 1983; COFORD 2004).

Side slope design and stabilization

Our review showed that fill slopes ($M = 106.6\%$) should be less pronounced than cut slopes ($M = 185.2\%$). However, this range was among the widest found in the analyzed documents, with *CV*s of 0.75 and 0.97 for the cut and the fill slopes, respectively. These differences can be explained by the different soil types, rock formations, and the dependence on prevailing climatic conditions in the considered regions, both of which were also considered in the analyzed documents, e.g., through tabular displays (Northern Forest Research Centre 1978; Oregon State University 2001). However, due to the complex relationships between these parameters, we see a need for further research to evaluate the failure/success of the design parameters regarding water management and stability, especially given the changing climate.

Stable side slopes are important for ensuring safe passage of vehicles, especially in hilly and mountainous regions (Kraebel 1936; NCHRP 2012). Climate change conditions make these requirements even more critical for fighting forest fires that are expected to occur more frequently (compare Fig. 1). Although changes to the side slopes of existing roads are difficult to implement, slope stability and water management could benefit from small changes, also due to the potentially reduced impact on subsurface flow (ibid.). Therefore, we argue that additional research on side slope stability and interactions between cut slopes and subsurface flow along forest roads is needed to mitigate the effects of climate change on hydrological processes and to continue to ensure access to forests for both wood supply and firefighting.

Ditches

Since the crowned cross-sectional profile was most recommended, ditches are necessary for drainage of run-off on the uphill side of the road. This is often realized with "V"-shaped ditches, wider than 0.6 m ($CV = 0.5$), deeper than 0.3 m ($CV = 0.33$), and with a cross-sectional slope of less than 75% ($CV = 0.67$). If a higher flow rate is required, the general trend is to use ditches in the form of a trapezoid, best armored with large stones, as the "U"-shaped ditch is considered unstable. This is critical in the context of climate change, as increased surface runoff and subsurface flow volumes are expected in the future (Fig. 1). However, it is also important to consider the relationship between ditch size, the frequency of ditch relief structures and cross-culvert dimensions. This means that if more or larger ditch relief culverts are used, possibly smaller ditches with lower discharge capacities may be required. Due to the lack of literature, we see a need for research of these relationships.

Ditch relief structures

With the crowned profile and ditches comes the need for ditch relief structures. The spacing of ditch relief structures is one of the more contentious design features analyzed in this review, (n = 19, see Fig. 7). Various factors are considered in the different guidelines as a basis for decision-making, with vertical alignment being the most important, used in 17 guidelines, followed by erosion potential (11) and expected precipitation (8). The factors gain significance in the context of climate change, especially in steep terrain, where the kinetic energy of water is the highest (Alabama Cooperative Extension System and Auburn University 2019; Valencia-Gallego and Montoya 2024). That is why spacing of ditch relief structures is probably one of the most efficient measures to adapt forest roads to climate change in terms of water management, while it provides several benefits related to other design features and can be realistically changed on existing roads.

Potential benefits are, for example, that higher runoff peaks are regularly diverted from the ditch, reducing the erosivity of such events along ditches and at culvert outlets, which can make the road more resilient (Piehl et al. 1988). In addition, water that is drained regularly into the forest stand on the downhill side of the road benefits the trees growing there (Toman 2004). Nevertheless, the benefits must be weighed against the costs of installing and maintaining additional culverts (Piehl et al. 1988). We identify a pressing need for research to determine adequate spacing under climate change conditions and its relationships to other design features, especially vertical alignment, cut-/fill-slope properties, slope and diameter of cross culverts, and ditch dimension.

An important design feature to be addressed is whether ditch relief may be discharged into streams. Ditches, especially those that intercept subsurface flow, can have a significant impact on the quantity and quality of water discharged into stream (Toman 2004). Therefore, we argue that disconnecting ditches of forest roads from streams has a great potential for reducing the impacts of climate change. This is also reflected in the number of guidelines that do not recommend the discharge of ditch water directly into the stream (n = 17) and advise a minimal spacing (n = 9, *median* = 25 m). Cross-drainage culverts should be spaced accordingly, and the integration of mitre drains (off-take-ditches, etc.) into the road design can also help to achieve this goal in flat terrain.

The distance of ditch relief structures from the nearest stream is also referred to as riparian buffer zones and is mentioned as such in some of the guidelines (Forest Management Branch 2004b; Mendocino CRCD 2015). More research is needed when considering riparian buffer zones along forest roads: Fixed riparian buffer widths, as analyzed in this review, may not always be implemented in forest management, as shown by Swartz et al. 2024. Also, forest owners may be disadvantaged by unevenly spaced streams in terms of costs due to loss of productive forest area or increased maintenance activities (Bakx et al. 2024). Besides funding, a fixed buffer width cannot be adapted to local needs, as Kuglerová et al. 2014 presented. Kuglerová et al. 2014 proposed site-specific widths of up to 50 m, which corresponded to the number found in this review, but did not analyze the specifics of forest roads (e.g., interception of sub-surface flow in ditches and its contribution to peak flows). If these were included in the criteria for decision-making about buffer width, the management of riparian buffer zones would become even more complicated but could potentially be adapted better to local requirements.

Water crossings

Typically, when planning water crossings, consulting engineers and state authorities are involved due to the complex and costly process (Oregon State University 2001; Forest Management Branch 2004b), which is why we see the least responsibility for climate change adaptation on part of the forest owners regarding these structures. In addition, the most obvious need for research is in water crossings. For example, various studies (Hosseinzadehtalaei et al. 2020; Martel et al. 2021) dealt with Intensity–Duration–Frequency curves and made specific recommendations for climate change adaptation, meaning that the need for investigation has already been recognized and taken up. Nevertheless, research should also address the special requirements along forest roads (e.g., low volume roads for year-round traffic by heavy timber trucks, gravel sedimentation, and wood debris) and the results should be included into guidelines such as those we have analyzed here.

Conclusions

This systematic review aimed to investigate the state of the practice of water management along forest roads and potentials for climate change adaptation. The research was conducted in three phases: (1st) identification of relevant design features of forest roads important for drainage and water management, (2nd) analysis of international legislation, guidelines, handbooks, and standards for these parameters, and (3rd) assessment of the potential for climate change adaptation of the analyzed design features by discussing current rhetoric found in supporting literature.

The analysis revealed that the parameters with the greatest potential for climate change adaptation are the (1) spacing of ditch relief structures, the (2) choice of ditch type, the (3) distance of ditch relief from streams (riparian buffer zones), and (4) dimensions of stream crossing structures. However, we identified an urgent need for further research on several design parameters and their relationships. For example, we were not able to dive deeper into each of the design features, e.g., into technical aspects of high complexity such as sizing of stream crossings, design of side slopes in light of different rock formations and soil types, or the relationship between ditch dimension, ditch relief spacing, and ditch relief culvert dimension. This review should be considered as a starting point for future studies that analyze such complex interrelationships for adapting road design in forests holistically. Analyses of paired watersheds could be a potential method for investigating different approaches in water management along forest roads.

As climate change will alter water regimes all over the world, consequences for water management in forest ecosystems cannot be overseen. Still, it seems as if opportunities for securing or retaining water resources within forests with the already existing infrastructure (i.e., roads), are not well studied. There is little information on the holistic performance of design parameters and their overall impact on road durability and water availability in surrounding forest stands. When changing climatic conditions are taken into account, it becomes clear that this aspect is of increasing importance to ensure the best possible water management for the future. Future research should start at this point by assessing road parameters given in standards in correlation with their local environmental conditions such as precipitation patterns, soil, or forest type. It is essential to include further geospatial information in order to ensure that measures are appropriate for specific local conditions. Follow-up studies could start by focusing on the design parameters we assessed here with the greatest potential for climate change adaptation.

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Declarations

Conflict of interest The authors declare no competing interests.

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