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**JOURNAL OF THE SOUTH AFRICAN INSTITUTION OF CIVIL ENGINEERING**

ISSN 1021-2019 (print) | ISSN 2309-8775 (online)
Vol 66 No 1, March 2024, Pages 2–11, Paper 1278

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**River water quality modelling in South Africa: Considerations, sourcing and accessing of input data**

C D Mahlathi, I C Brink, J M Wilms

River water quality modelling relies on a good dataset for model input, calibration and validation to develop a reliable model. Determination of data requirements, and data sourcing towards this purpose in South Africa, are not elementary. Data availability is key throughout the modelling processes, making the sourcing of good data equally imperative. This paper provides starting considerations, and compiles a list of available data sources applicable to river water quality modelling in South Africa. It also provides a background on the included data sources and a general overview of the extent of the databases.

**Keywords:** calibration, validation, water quality data, hydrodynamic data, database

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**INTRODUCTION**

Water quality modelling in South African rivers requires compliance with certain standards for both hydrodynamic and water quality data, as determined by the precision and accuracy needed for the model's output and the modelling goals (Daggupati et al 2015; Guillaume et al 2019). The availability and quality of data should be assessed early in the modelling process to inform the approach and to limit complexities. It is crucial to ensure that sufficient and appropriate data is present to generate realistic estimates of the desired model parameters (Guillaume et al 2019).

Modellers must investigate the quality and quantity of available data in the early stages of the modelling process to ensure suitability for modelling goals. However, sourcing relevant and accurate data for river water modelling in South Africa can be challenging. Modellers often encounter uncertainties in model choice and modelling goals, as well as uncertainties in where and how to begin the modelling process.

South Africa has a comprehensive river monitoring network and system, which is publicly available and organised by the South African Departments of Human Settlements, and Water and Sanitation. This covers major river systems in the country and includes flow gauges, rain gauges and water quality sampling. Despite the extent of the network, data gaps can occur due to equipment breakdowns and outdated data (Slaughter et al 2017). Additional data collected by third parties and private companies to fill gaps in certain regions can be requested at a cost.

The assessment of water quality using established field-based techniques is commonly acknowledged for its precision, given the up-close examination of water quality factors. Nonetheless, this method is prohibitively expensive and unworkable when it comes to overseeing large geographical areas (Modiegi et al 2020). In recent years, the monitoring of water quality data in South Africa has steadily decreased, particularly since 2010, due to rising costs and a budget that has not kept up with monitoring needs, combined with a lessened capacity to adhere to sampling frequencies, leading to the closure of several monitoring stations (Silberbauer 2020).

The decline in water quality data monitoring has far-reaching implications for the management and protection of South Africa’s water resources. This reduction in monitoring capacity reduces the ability to detect changes in water quality in a timely manner and to then respond accordingly.
Recommended temporal resolutions for modelling natural river processes (extracted from Baffaut et al 2015 and used here with permission)

<table>
<thead>
<tr>
<th>Process category</th>
<th>Relevant time scales</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Seconds</td>
</tr>
<tr>
<td>Water movement</td>
<td></td>
</tr>
<tr>
<td>Nutrients and other agrochemicals</td>
<td></td>
</tr>
</tbody>
</table>

The choice of the modelling approach is influenced by the intended purpose or goal of the model, shaping the direction in which the modelling process is undertaken (Tredennick et al 2021). The data requirements of each approach may vary, depending on the complexity and processes of the modelling environment (empirical versus mechanistic). Insufficient data may impact the reliability and validity of results.

**Model resolution**

Model resolution covers the spatial and temporal aspects of the environment that is modelled. The first step in model creation is to assess data needs in terms of quantity, quality and resolution to ensure accuracy and reliability. Planning for final validation and calibration is critical. However, limitations in available data may impact initial modelling decisions, such as generating data, using mathematical methods, or adjusting goals and strategy based on the limited data. Outcomes from two key reviews by Baffaut et al (2015) and Daggupati et al (2015) summarise calibration and validation strategies for variable data availability scenarios and serve as examples of considerations, but do not constitute a comprehensive summary of all information sources on the topic. Baffaut et al (2015) highlight spatial and temporal considerations for hydrologic and water quality models. Tables 1 and 2 were extracted from these sources to summarise the temporal and spatial resolutions for modelling various water environments and water quality parameters.

In Table 1 processes active over a range of spatial scales are presented (the + symbol indicates that the processes simulated at smaller scales remain active at the current scale). The spatial resolution of the model can be determined by the size of the river reaches segmentation, subjective to the modelling objectives. This should be the smallest spatial element which the model output should represent.

The study recommends having representative input and calibration data available at a spatial and temporal extent and resolution that align with the model and study objectives. The model should be calibrated in successive steps, matching the critical processes and modelling the objectives’ spatial and temporal resolutions.

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**Table 1** Spatial resolution recommendation table relevant to river models (relevant table section extracted from Baffaut et al 2015 and used here with permission)

<table>
<thead>
<tr>
<th>Process category</th>
<th>Point (&lt; 1 m²)</th>
<th>Small catchment (100 m² to 50 ha)</th>
<th>Watersheds (50 ha to 50 km²)</th>
<th>River basin (&gt; 50 km²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water movement</td>
<td>Runoff generation, infiltration, evapotranspiration, perched water table, and preferential flow</td>
<td>Concentrated flow, subsurface flow, drainage, buffers, ponds, wetlands, variable source areas, exfiltration, and interflow</td>
<td>+ Streamflow, bank storage, riparian areas, groundwater flow, aquifer recharge, flood plain, point discharges, and water withdrawals</td>
<td>+ Reservoirs and major hydraulic structures</td>
</tr>
<tr>
<td>Nutrients and other agrochemicals</td>
<td>Soil/plant interactions; leaching to perched, shallow, and deep aquifers; sorption, transformation, and degradation in vadose zone and shallow aquifers</td>
<td>+ Transport with drainage and subsurface flow, transformations and degradations in ponds and wetlands</td>
<td>+ Stream transport, water/air and water/streambed exchanges, in-stream transformations and degradation, riparian area, algae and aquatic plants, and point discharges</td>
<td>+ Cycling in major hydraulic structures</td>
</tr>
</tbody>
</table>

---

**Table 2** Recommended temporal resolutions for modelling natural river processes (extracted from Baffaut et al 2015 and used here with permission)

<table>
<thead>
<tr>
<th>Process</th>
<th>Relevant time scales</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Seconds</td>
</tr>
<tr>
<td>Infiltrations</td>
<td>✔️ │ ✔️ │ ✔️ │ ✔️ │ –    │ –     │ –     │ –     │ –</td>
</tr>
<tr>
<td>Evapotranspiration</td>
<td>–     │ ✔️ │ ✔️ │ ✔️ │ –    │ –     │ –     │ –     │ –</td>
</tr>
<tr>
<td>Preferential flow</td>
<td>✔️ │ ✔️ │ ✔️ │ ✔️ │ –    │ –     │ –     │ –     │ –</td>
</tr>
<tr>
<td>Soil moisture redistribution</td>
<td>–     │ ✔️ │ ✔️ │ ✔️ │ ✔️ │ –     │ –     │ –     │ –</td>
</tr>
<tr>
<td>Runoff/overland</td>
<td>–     │ ✔️ │ ✔️ │ ✔️ │ ✔️ │ –     │ –     │ –     │ –</td>
</tr>
</tbody>
</table>

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Continued on page 4 →
Tables 1 and 2 can be used as a guide to regulate the input data required for models. Data quality and quantity required for model calibration and validation can be discerned from the recommended calibration and validation processes available for application at the preference of the modeller.

**Model calibration and validation**

Daggupati *et al* (2015) recommends a guideline for calibrating and validating hydrodynamic and water quality models. The guideline includes careful consideration, execution, and documentation of the three major calibration and validation elements, as listed in Table 3.

Elements 2 and 3 of the calibration and validation guidelines are linked to data quality and quantity requirements, as highlighted in this paper for South African data sources. Further details on each element can be found in the source article by Daggupati *et al* (2015). The allocation of available data for model validation and
calibration requires splitting the data into two parts, and various data allocation methods exist in literature, such as temporal split-sample, spatial proxy basin, differential split-sample, and proxy basin differential split-sample. The reader is referred to Daggupati et al (2015) for more information.

The aim of this paper is to guide the selection of data sources for water quality modelling in South African river systems. However, before sourcing data, it is crucial for the modeller to comprehend the data requirements of the model as prescribed by relevant studies and guidelines, such as those discussed by Daggupati et al (2015) and Baffaut et al (2015).

Additionally, validation of water quality models can also be done using long-term simulations and frequency distributions. This involves comparing the simulated results with the available observed data. One approach to calibrate water quality models using long-term simulations and frequency distributions is through a method known as “split-sample validation”. The prevalent method for split-sample validation in the literature is the two-period approach, which involves dividing the calibration and validation periods into roughly equal sections. This technique offers the advantage of ease of implementation and minimising model runtime, particularly beneficial for computationally intensive hydrological and water quality models (Arsenault et al 2018). Another approach is to use a Monte Carlo simulation, which uses random sampling from the frequency distribution of the input data to generate multiple realisations of the model output (Atiem & Harmanciólü 2006). The model is then calibrated by comparing the frequency distribution of the observed data to the distribution of the model output generated by the Monte Carlo simulation. A decision on which method is suitable for a specific application can be determined by the purpose of the study and further consultation with relevant literature.

### Model environment and water quality parameters

To accurately model water quality in rivers and reservoirs, different data sets and understanding of processes are required. Rivers require continuous monitoring of water quality parameters, and an understanding of the transport of water and pollutants within the river. On the other hand, modelling water quality in reservoirs requires an understanding of storage, mixing, and release of water, as well as interactions with the surrounding environment, and often requires more diverse and detailed data sets such as bathymetric data, meteorological data, and information on water inputs and outputs. These differences in data requirements reflect the unique challenges and complexities of modelling water quality in each system.

The differentiation between the data requirements for non-conservative and conservative water quality parameters in river systems is based on the type of water quality parameters being modelled. Water quality parameters, whether conservative or non-conservative, are subjected to distinct modelling approaches. Conservative water quality parameters, like total dissolved solids, maintain a consistent concentration in the water column and do not engage in chemical interactions with the environment. Hence, proxy parameters, like electrical conductivity levels, are observed and linked to variations in the concentration of conservative parameters within the river system. This approach is widely noted in the majority of water quality parameter studies found in the literature (Ranjith et al 2019). In contrast, non-conservative water quality parameters, like nutrients, can interact chemically with the environment, causing concentration changes over time. Modelling non-conservative water quality parameters, as demonstrated by reviewed assessments of fate and transport models (Addis et al 2023), necessitates the acquisition of high-quality measurement data. This data should encompass information on the sources and sinks of these substances, providing a comprehensive understanding of the intricate processes governing their behaviour in river systems.

In conclusion, the data requirements for modelling non-conservative water quality parameters in rivers are more complex and extensive compared to those for modelling conservative water quality parameters.

The data requirements for representing point and non-point sources of pollution loads in water systems also differ. Point sources refer to identifiable sources of pollution, such as wastewater treatment works, whereas non-point sources refer to diffuse sources of pollution, such as agricultural runoff. To accurately model point sources, detailed data on their discharge characteristics and the pollutants they release into the water system is required. This data may be obtained from monitoring and reporting systems, as well as regulations and guidelines for wastewater treatment works. In South Africa it is likely that data on wastewater treatment works is available through various sources, including governmental organisations and public utilities. However, further research and investigation may be needed to determine the availability and accuracy of such data.

### SOUTH AFRICAN RIVER MODELLING DATA SOURCES

The Water Research Commission (WRC) in South Africa can provide valuable data resources for water quality modelling. The WRC has a daily rainfall database up until 2000 (Lynch 2004), as well as a database of daily air temperature (Schulze & Maharaj 2004), which can be useful for hydrologic and meteorological applications in water quality modelling. These databases provide valuable information for researchers and modellers looking to understand the impacts of weather and climate on water quality in South Africa.
Data sources for river modelling in South Africa include both free and paid options from public and independent sources. The South African Department of Water Affairs (DWA) water quantity and quality monitoring network is a primary data source for water quality models, as reported and utilised in studies by Dabrowski (2014), Mahlathi et al (2016) and Slaughter et al (2017). It contains measuring station data for 19 water management areas, as shown in Figure 1.

This database can be accessed through the DWA website or dashboard online. Its network of monitoring stations covers most of the river systems in the country, but data augmentation may be required in certain cases, depending on the modelling purpose (Slaughter 2017). Independent sources are available and can be explored to augment data where needed. These data sources are summarised in Table 4 and discussed in more detail.

**Climate and weather**

Climate and weather data includes precipitation, air temperature, solar radiation, relative humidity, and wind speed data. This information is required as input for most mainstream water quality models.
Table 5 Modified SAWS countrywide observational network – number of stations with data relevant to river water quality modelling (Source: South African Weather Service (SAWS 2023))

<table>
<thead>
<tr>
<th>Station type</th>
<th>Number of stations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automatic weather stations (AWS)</td>
<td>231</td>
</tr>
<tr>
<td>Climate stations</td>
<td>12</td>
</tr>
<tr>
<td>Rainfall stations</td>
<td>1180</td>
</tr>
<tr>
<td>Automatic rainfall stations</td>
<td>153</td>
</tr>
<tr>
<td>Sea surface temperature stations</td>
<td>23</td>
</tr>
<tr>
<td>Meteorological radar systems</td>
<td>14</td>
</tr>
<tr>
<td>Global atmospheric watch station</td>
<td>1</td>
</tr>
<tr>
<td>Dobson ozone spectrophotometer station</td>
<td>2</td>
</tr>
<tr>
<td>Baseline surface radiation network station</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 6 Temporal extent and resolution of SAWS climatic data for water quality modelling purpose (Source: South African Weather Service (SAWS 2023))

<table>
<thead>
<tr>
<th>Data type</th>
<th>Temporal resolution</th>
<th>Temporal extent (starting year until present)</th>
<th>Stations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainfall values</td>
<td>daily</td>
<td>1836</td>
<td>all</td>
</tr>
<tr>
<td>Surface observations</td>
<td>daily</td>
<td>1884</td>
<td>some</td>
</tr>
<tr>
<td>Wind speed and direction</td>
<td>hourly</td>
<td>1950</td>
<td>all</td>
</tr>
<tr>
<td>Temperature</td>
<td>hourly</td>
<td>1950</td>
<td>all</td>
</tr>
<tr>
<td>Humidity</td>
<td>hourly</td>
<td>1950</td>
<td>all</td>
</tr>
<tr>
<td>Pressure</td>
<td>hourly</td>
<td>1950</td>
<td>all</td>
</tr>
<tr>
<td>Satellite data</td>
<td>unknown</td>
<td>1992</td>
<td>-</td>
</tr>
<tr>
<td>Radar</td>
<td>unknown</td>
<td>1994</td>
<td>-</td>
</tr>
</tbody>
</table>

models such as Soil Water Assessment Tool (SWAT), Water Quality Analysis Simulation Program (WASP) and Qual2kw. Numerous sources with datasets ranging from early 1920 up to the present exist in digital libraries. Examples of these libraries are the United States of America’s National Oceanic and Atmospheric Administration (NOAA), and the local databases: the WRC daily rainfall and gridded daily temperature database and the South African Weather Service (SAWS). The SAWS database contains the most South African weather and climate data and is discussed further below.

SAWS
Tables 5 and 6 were created using the information on the SAWS climate data page to respectively display the countrywide observational network (Table 5), and the temporal extent and resolution of the available climatic data (Table 6).

Data can be accessed through a data enquiry. The SAWS website can be used to determine the correct information and the station of interest. The processing time for data requests varies depending on the type, time frame and extent of the data. The SAWS climate database, which stores the data, can be accessed by clients for a fee, with different pricing for commercial and non-commercial use. It is possible that students may have access to the data at no cost. Rainfall station data, useful for predicting river flow, is also available. Resale of purchased data is not allowed and information on the SAWS Data Policy can be found on the website. SAWS provides weather data through its web-based tool, hydroNET, which uses data and models to make predictions. Documentation on data collection, processing and reporting is available on the data portal to support data reliability.

Stream hydrogeometry
Stream hydrogeometric data includes hydrologic and geometric info (Chapra 1997). No comprehensive database has been found, so methods of estimation are provided. Site-specific literature may contain limited data for specific study areas. Digital tools (ArcGIS, QGIS) for measuring and estimating river characteristics are available for use by modellers.

The Department of Water and Sanitation – National Integrated Water Information Systems (DWS-NIWIS) website offers Google Earth files of the entire South African river network. The files can be viewed on Google Earth with measuring tools. For missing data, estimation techniques like point estimate, river reach estimate, low-flow analysis, discharge coefficients, and Manning’s equation are recommended by Chapra (1997).

Land use and land cover
Land cover data can be determined by analysing satellite and aerial imagery, which captures coverage in the region (forests, wetlands, impervious surfaces, agriculture, and other land and water types) (NOAA 2020). The South African National Land-Cover Dataset (SANLCDS) serves as one of the main suppliers of land use and land cover data in South Africa. The dataset has been generated from 20-metre resolution multi-seasonal Sentinel 2 satellite imagery which represents the current full temporal range of available imagery (SANLCDS 2018).

Data can only be accessed once an account is created on the download link. Land use and land cover models are applied to study water quality in catchments and rivers with examples such as the work of Tahiru et al (2020). The work of Petersen et al (2017) is an example of a South African study. Additionally, Slaughter and Mantel (2017) used data from the South African National Land-Cover Dataset (SANLCDS) on land cover models to predict non-point nutrient inputs into rivers.

Hydrodynamic data
Table 4 (see page 6) lists sources used to estimate river flows for hydrodynamic models. The data includes geographic, hydrodynamic properties, river flows, rainfall, point source discharges and water extraction. Two main data portals for hydrodynamic data are discussed.

The Global Runoff Data Centre (GRDC) (2020) is an international data repository functioning under the patronage of the World Meteorological Organisation (WMO). The database holds global hydrodynamic data, including from South Africa’s public and private monitoring networks like the Department of Water.
and Sanitation. Data can be viewed for free on the GRDC portal, but downloading requires a written motivation. Requests for specific river station data can be filtered by region.

For South Africa, applying the country filter produces a map (Figure 1 on page 6) with all 317 stations (Lesotho and Swaziland included). Available data including statistics (percentage missing monthly and daily data, data period range and catchment area) can be seen by clicking on a station point on the map (Figure 2). In addition to the detailed display of station data, a graph that plots the time series of flow data over the range of the station data is displayed, which allows for quick observations of the time periods with gaps (Figure 3). The spatial and temporal resolution of the data vary for different sections, for example the Olifants River, which has more high-resolution data because of the number of studies (Ashton & Dabrowski 2011; Baker et al 2011; Dabrowski 2014; Mahlathi et al 2016; Slaughter et al 2017; Udall 2018) and projects conducted in the region.

The GRDC site provides runoff data for river hydrodynamic model calibrations and verifications, making it a valuable resource for water quality models. Its validity and reliability are ensured through collaboration with national water agencies like South Africa’s Department of Water and Sanitation. Data usage guidelines, including restrictions on distribution and commercial use, are stated on the GRDC website. Additional guidelines on the use and determination of data are detailed in the document titled Global Runoff Data Centre (GRDC 1995) that is received when access is requested.

**DWS-NIWIS**

The South African National Integrated Water Information System portal

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**Figure 2** GRDC web portal for hydrodynamic data stations displaying station locations on the map

**Figure 3** Data portal showing station details and river flow data visualisation in a form of time series plots
(DWS–NIWIS 2015) is an online platform managed by the Department of Water and Sanitation. It provides information products through dashboards and a web GIS interface that displays maps and locations of data stations for Surface Water, Ground Water, and Water Quality monitoring networks. The platform facilitates efficient analysis and reporting of water data across South Africa. The Water Quantity dashboard provides access to hydrodynamic data, including river flows, surface water storage, groundwater availability status, groundwater level status, and water transfers. Figure 4 refers.

**River flow data**
The DWS–NIWIS dashboard displays river flow data for 19 water management areas, with a varying number of stations. Verified river flow data is graphically depicted, with colour codes indicating low- to high-flow systems, as shown in Figure 5, and unverified data is available on the main database. The graphical representation allows users to easily identify the flow conditions of a particular river.

River flow data can be downloaded directly from the dashboard in the form of a .csv, .xls or .pdf file. The file contains date columns corresponding to river flow rates.

In addition, there are columns showing high-, moderate- and low-flow rates.

In the absence of a good set of measured hydrodynamic data, the WRC 2012 website provides comprehensive data, information, tools and models (Pitman and ACRU hydrological models, and the WRYM, WRPM, WReMP water management models) for water resource practitioners to study and plan their water resources. The website features GIS maps, the WRSM2000 (Pitman) rainfall-runoff model, and various databases, reports and spreadsheets. The WRSM model, managed by Allan Bailey, determines catchment-based rainfall, calibrates simulated flows against observed data, and produces naturalised flows and present-day flows. To fully understand the model and information system, it is recommended to attend the WRSM/Pitman and WRC 2012 information system courses; course schedule information can be obtained from Allan Bailey of Bailey and Pitman Water Resources (Pty) Ltd at allankb@netactive.co.za. Access to the website requires registration.

Temporal and spatial data augmentation methods may be required to correct the temporal resolutions of data from monthly to daily. Sources such as Slaughter et al (2015), and Hughes and Slaughter 2015 provide methods for disaggregation of flow data from monthly to daily flows. Recently, the work of Mahlathi et al 2022 details the impact of model input data augmentation methods on model output that can be used to evaluate some data augmentation methods.
Water quality data

Water quality data is necessary to set up, calibrate and validate river water quality models. The data covers biological parameters (e.g. biological oxygen demand), chemicals (e.g. dissolved oxygen), and physical characteristics (e.g. water temperature). The main source of water quality data in South Africa is DWS-NIWIS and additional data can be obtained from third-party sources at a fee.

Water quality data can be obtained in a similar manner as hydrodynamic data. The water quality data is available on the water quality monitoring dashboard, which displays 4,457 monitoring stations. The stations are displayed on a table and GIS interface.

The portal provides a GIS interface with water quality data from monitoring points in South Africa. By selecting the river system on the map, users can access data for each station, including water quality information, as well as the locations and compliance data of wastewater treatment plants. Data can be viewed in a graph or downloaded in a .csv file.

Remote sensing data and other sources

In the context of river water quality modelling in South Africa, remote sensing data is a valuable resource. This data, including satellite imagery, aerial photography and hyperspectral data, provides insight into various water quality parameters, such as temperature, turbidity, dissolved oxygen and chlorophyll concentration. In the application of data various analysis and models can be created to estimate water quality parameters, as applied in various studies in literature (Van Deventer et al 2018; Li et al 2020; Seaton et al 2020; Adjovu et al 2023). However, it is crucial to combine remote sensing data with ground-based measurements. The drawback is that there is a lack of in situ data due to site cost, as well as a lack of high-level technical expertise, particularly in sub-Saharan Africa, for water quality monitoring (Adjovu et al 2023).

The spatial and temporal scales of remote sensing data that can be used for water quality modelling of river systems in South Africa are dependent on the type of data and the sensor utilised. Spatial resolution, a crucial factor in satellite imaging, defines the smallest real-world object captured in a two-dimensional image, determining the applicability of the product. High-resolution satellite imagery and aerial photography excel at small-scale detail, whereas lower-resolution satellite imagery offers information at a larger scale with reduced detail (Valenzuela et al 2022).

The frequency of satellite overpasses, and the duration between acquisitions, significantly influence the temporal scale. While certain satellites furnish daily data, others cover an area only every few days or even weekly. Satellites with high resolution and a brief revisit time provide more frequent observations, enhancing the temporal scale (Trezza et al 2018).

It is essential to consider both the spatial and temporal scales when choosing remote sensing data for water quality modelling in South African river systems. The ideal spatial and temporal resolution will depend on the goals and requirements of the modeling project. For instance, high-resolution data may be necessary to accurately capture fine-scale changes in water quality, while lower-resolution data may be adequate for monitoring large-scale trends.

CONCLUSION

The process of finding data that suits the modelling requirement for a South African river system is not obvious. This paper therefore provides a guideline for accessing available river modelling data sources, and discusses relevant starting considerations. Applying this knowledge may save time during the modelling exercise by directing the modeller to initial considerations. Applying this knowledge may save time during the modelling exercise by directing the modeller to initial considerations.

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INTRODUCTION
Overloading has been recognised as both a safety concern and a cost concern. Overloading occurs when a vehicle is loaded beyond its maximum legal weight (Yassenn et al 2015). Damage to roads as a result of overloading leads to higher maintenance and repair costs, and shortens the life of a road (Hornych 2015; Shahul & Prathap 2018). Consequently, these costs are carried by the road user if overloading is not controlled. Previous studies have shown that this condition escalates when the control of traffic is poor (Rys et al 2016). It has been found that legally loaded heavy vehicles cause a relatively small amount of damage to road pavement structures, as opposed to overloaded heavy vehicles which are responsible for approximately 60% of the damage to roads in South Africa (CSIR 1997). Roads are designed based on an assumed projected traffic load and volume. In the pavement design process, overloading is usually not taken into account and thus any heavy vehicle overloading damages the structural design period (SDP) of a pavement (CSRA 1996). The SDP for roads in Namibia ranges from 7 to 30 years depending on the road categories. The SDP for the various road categories are as follows:
- Class A roads (SDP between 15 and 30 years)
- Class B roads (SDP between 15 and 25 years)
- Class C roads (SDP between 10 and 20 years)
- Class D roads (SDP between 7 and 15 years) (CSRA 1996; RA 2014).

The Namibian road network consists of 8 250 kilometres of paved roads out of a total of 48 900 kilometres of road.

Analysis of the extent of heavy vehicle overloading on Namibian trunk roads and evaluation of the effectiveness of existing mitigation measures

G Agoro, P Johannes, R Ambunda

Overloading of heavy vehicles reduces pavement life and increases pavement life cycle costs. As part of Namibia’s strategy to control heavy vehicle overloading on the road network, weighbridge facilities have been constructed at strategic locations on primary routes (trunk roads). The study analysed the extent of heavy vehicle overloading on Namibian trunk roads, as well as the effectiveness of existing overloading mitigation measures. The dataset comprised heavy vehicle loading information from the year 2015 to 2019, from ten static weighbridge facilities. The parameters investigated include overloading magnitude, the effect of overloading on road pavement life, and the effectiveness of current overload mitigation measures. The results showed that 13.3% of the vehicles weighed were overloaded, with a compounded decrease in overloading of approximately 0.5% per annum. Despite the overloading decrease, the study found that the estimated road service life was reduced by as much as nine years over the study period. High levels of weighbridge avoidance and poor stakeholder coordination in mitigating overloading were identified. The study recommends deploying high-speed weigh-in-motion systems, an increase in fines charged for overloaded offenses, and developing a demerit point-based system for habitual offenders to strengthen mitigation measures.

Keywords: overloading, heavy vehicles, vehicle classification, axle loads, weighbridges
The biggest threat to the paved road network is the prevalence of heavy vehicle overloading across the road network (Kiggundu & Lutombi 2004). Previous studies by Kiggundu and Lutombi (2004) and Pinard (2010) reported an average overloading rate between 20% and 29% on Namibian trunk roads between the years 2000 and 2010. Recognising the need for an effective overloading strategy for Namibia, the Roads Authority of Namibia (RA) built ten static weighbridge stations on the trunk road network – Class B and Class C roads (Kemp et al. 2018). Despite the overloading mitigation strategy, there has been added pressure on the entire road network due to an increase in weighbridge route avoidance (poor compliance) by heavy vehicle operators, and an observed increase in overloading (RA 2020).

Although Namibia has introduced heavy vehicle overloading detection measures, a knowledge gap exists regarding the extent and impact of overloading on Namibian roads and the effectiveness of the current alleviation measures. To this end, the goal of this study was to quantify the level of overloading on Namibian roads from 2015 to 2019. Furthermore, the study assessed the changes in heavy vehicle characteristics, and evaluated the effectiveness of both existing overloading detection and mitigation measures. Thus, the study employed both qualitative and quantitative approaches. The heavy vehicle axle loading data and overloading volume were collected from the weighbridge records and systems of the RA. Information, such as fines imposed due to overloading, was collected from survey questionnaires and from desktop literature reviews.

### DATA

#### Heavy vehicle (HV) traffic and loading data

Heavy vehicle (HV) overloading data for the period 2015 to 2019 was obtained for all the weighbridge stations (see Figure 1) for the different HV classes (see Table 1). HVs were classified according to Bosman’s classification system. This system classifies HVs based on the traffic loading characteristics of South African HVs (Bosman 2004), with seven main classes shown in Table 1. HVs were classified according to Bosman’s classification system. This system classifies HVs based on the traffic loading characteristics of South African HVs (Bosman 2004), with seven main classes shown in Table 1. Bosman’s classification system was applied in the study as it adequately captured the different HV axle load configurations recorded by Namibian weighbridges.

The names of the weighbridges that were studied, the route names on which the weighbridges are located (see Figure 1) and their strategic importance in serving traffic (commercial or otherwise) from neighbouring countries are indicated in Table 2 (on page 14). The study obtained the HV overloading data from the TRAFMAN vehicle system (vehicle reports) at the Roads Authority of Namibia (RA) for the period from 2015 to 2019.

The data collected from the TRAFMAN vehicle system included overloaded heavy vehicles (HV) volumes, HV axle configurations, HV axle loads, and the punitive measures and amounts of traffic fines issued for overloading.

#### Effectiveness of the overloading mitigation measures

The study conducted questionnaire interviews at all ten weighbridge stations operated by the Roads Authority of Namibia (RA). The questionnaire served as a tool to evaluate the effectiveness of the existing mitigation measures and strategies for curbing heavy vehicle (HV) overloading on the selected road classes. The questionnaires were developed to investigate the following:

- The frequency of weighbridge avoidance
- The impact of existing strategy in discouraging non-compliance with HV axle loading regulation

---

**Table 1 Heavy vehicle (HV) axle classification (Bosman 2004)**

<table>
<thead>
<tr>
<th>Vehicle class</th>
<th>Axle load configuration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 2 (2 axles)</td>
<td>1-1</td>
</tr>
<tr>
<td>Class 3 (3 axles)</td>
<td>1-1-1</td>
</tr>
<tr>
<td>Class 4 (4 axles)</td>
<td>1-1-1-1</td>
</tr>
<tr>
<td>Class 5 (5 axles)</td>
<td>1-1-1-1-1</td>
</tr>
<tr>
<td>Class 6 (6 axles)</td>
<td>1-1-1-2</td>
</tr>
<tr>
<td>Class 7 (7 axles)</td>
<td>1-1-2-1</td>
</tr>
<tr>
<td>Class 8 (8 axles)</td>
<td>1-1-3</td>
</tr>
<tr>
<td>Class 9 (9 axles)</td>
<td>1-2-1-1</td>
</tr>
<tr>
<td>Class 10 (10 axles)</td>
<td>1-2-1-2</td>
</tr>
<tr>
<td>Class 11 (11 axles)</td>
<td>1-2-1-3</td>
</tr>
<tr>
<td>Class 12 (12 axles)</td>
<td>1-2-2-1</td>
</tr>
<tr>
<td>Class 13 (13 axles)</td>
<td>1-2-2-2</td>
</tr>
<tr>
<td>Class 14 (14 axles)</td>
<td>1-2-2-3</td>
</tr>
<tr>
<td>Class 15 (15 axles)</td>
<td>1-2-2-4</td>
</tr>
</tbody>
</table>

---

**Figure 1 Weighbridge locations and road classification (NSA 2017)**
The adequacy and impact of HV overloading fines on curbing non-compliance.

**METHOD**

**Coefficient of determination for traffic growth analysis (overloading trend)**
The study applied summary statistics and simple linear regression coefficient of determination ($R^2$), as a goodness-of-fit measure, to assess the degree of HV overloading between 2015 and 2019, at a 95% confidence interval. The coefficient of determination was determined using Equation 1 (Dufour 2011).

$$R^2 = 1 - \frac{SSR}{SST} \quad (1)$$

Where:
- $SSR$ = sum squared regression
- $SST$ = total sum of squares.

The probability value ($p$-value) test was also done to determine the level of statistical significance of the HV overloading trend. A $p$-value less than 0.05 ($≤0.05$) indicates that the trend is statistically significant.

**Calculation of E80s / heavy vehicle (HV) axle**
The study quantified the road damage on the selected road classes caused by the various wheel loads by converting mixed traffic axle loads to an equivalent number of "standard" loads – equivalent standard axle loads 80 kN (E80s). The conversion was done using the Fourth Power-Law represented by Equation 2 (CSRA 1996).

$$F = \left( \frac{P}{80} \right)^n \quad (2)$$

Where:
- $n$ = relative damage exponent
- $F$ = load equivalency factor (LEF)
- $P$ = axle load in kN.

The average E80s / HV were computed for each class of HVs with two to eight axles (see Table 1) using Equation 3.

$$\frac{E80}{HV} = \frac{\sum F}{n} \quad (3)$$

Where:
- $F$ = load equivalency factor (LEF) from Equation 2
- $n$ = total number of heavy vehicles.

**Estimation of road service life due to HV overloading**
Heavy vehicle overloading accelerates the decline of the road’s design life (Mulyono et al 2010). The impact of HV overloading on the service life of the road was determined by calculating the decline rate in the road service life cycle using Equation 4 (CSRA 1996). The equivalent standard axle loads (ESALs) for normal and overloaded axles were determined using Equation 2.

$$SL = \left[ \frac{ESAL_{NORMAL}}{ESAL_{OVERLOAD}} \right]^{DL} \quad (4)$$

Where:
- $SL$ is the actual service lifetime (years)
- $DL$ is the design lifetime (years)
- $ESAL_{NORMAL}$ is the equivalent number of normal loaded HV traffic
- $ESAL_{OVERLOAD}$ is the equivalent number of overloaded HV traffic.

**Effectiveness of the existing overloading mitigation measures**
The study developed a questionnaire to assess the effectiveness of existing overloading detection and mitigation measures in the regulation and at the weighbridge stations. The questionnaires focused on the following aspects:
- Weighbridge compliance (use and axle load compliance by HV operators)
- Weighbridge operations
- Relationship between stakeholders in curbing HV overloading practices.

**RESULTS AND DISCUSSIONS**

Heavy vehicles (HVs) overloading magnitude and trend in Namibia
The study found that a total of 218 546 heavy vehicles (HVs) out of a total of 1 642 254 HVs weighed between 2015 and 2019 were found to be overloaded. This represented an average degree of overloading of approximately 13%. The detailed results for the ten weighbridges are given in Figure 2.

The Walvis Bay weighbridge station was observed to have the highest percentage of HV overloading, with 25% of all HVs recorded identified as overloaded over the study period. The Oshivelvo, Katima Mulilo, Ariamsvlei, Brakwater, Gobabis, Rosh Pinah and Onhuno weighbridge stations recorded overloading magnitudes between 21% and 6%. The lowest percentage of overloaded HVs was observed at the Noordoewer weighbridge station, accounting for 6% of the total vehicles weighed over the study period.

The aggregate overloading trend for all ten weighbridges was calculated from 2015 to 2019 (see Figure 3). The study applied a simple linear regression analysis to the data. The coefficient of determination ($R^2$) was used to define the best fit linear regression trend line for HV overloading between 2015 and 2019.

The coefficient of determination indicates that the HV traffic

---

**Table 2 Route names and information on weighbridge stations on the Namibian road network**

<table>
<thead>
<tr>
<th>Weighbridge station name</th>
<th>Route name</th>
<th>Route number</th>
<th>Strategic importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grootfontein</td>
<td>Grootfontein – Otavi</td>
<td>B8</td>
<td>Connects Namibia to Zambia, Botswana and Zimbabwe</td>
</tr>
<tr>
<td>Katima Mulilo</td>
<td>Kongola – Katima Mulilo</td>
<td>B8</td>
<td>Connects Namibia to Zambia and Botswana</td>
</tr>
<tr>
<td>Brakwater</td>
<td>Windhoek – Okahandja</td>
<td>B1</td>
<td>Connects Namibia to South Africa, Zambia, Botswana and Zimbabwe</td>
</tr>
<tr>
<td>Oshivelvo</td>
<td>Oshivelvo – Omuthiya</td>
<td>B1</td>
<td>Connects Namibia to DRC and Angola</td>
</tr>
<tr>
<td>Oshikango</td>
<td>Oshikango – Onangwua</td>
<td>B1</td>
<td>Connects Namibia to DRC and Angola</td>
</tr>
<tr>
<td>Rosh Pinah</td>
<td>Noordoewer – Rosh Pinah</td>
<td>C13</td>
<td>Connects Namibia to South Africa</td>
</tr>
<tr>
<td>Noordoewer</td>
<td>Keetmanshoop – Noordoewer</td>
<td>B1</td>
<td>Connects Namibia to South Africa</td>
</tr>
<tr>
<td>Ariamsvlei</td>
<td>Ariamsvlei – Karasburg</td>
<td>B3</td>
<td>Connects Namibia to South Africa</td>
</tr>
<tr>
<td>Walvis Bay</td>
<td>Walvis Bay – Swakopmund</td>
<td>B2</td>
<td>Connects Namibia to Zambia, Botswana and Zimbabwe</td>
</tr>
<tr>
<td>Gobabis</td>
<td>Buitepost – Gobabis</td>
<td>B6</td>
<td>Connects Namibia to Botswana and Zimbabwe</td>
</tr>
</tbody>
</table>
growth regression model represents 77% of the variance in the HV overloading trend at a 95% confidence interval. In all, the study observed a statistically significant \( p < 0.0048 \leq 0.05 \) cumulative reduction of 0.5% per year in HV overloading normalised against HV volumes over the study period.

**Analysis of the HV traffic characteristics**

The study interrogated the vehicle characteristics (HV volumes) trend over the study period (2015 to 2019), considering the decreasing overloading trend over the same period (see Figure 3). It was observed that, while overloading slightly reduced over the study period, the overall volume of HV vehicles recorded at the weighbridge stations increased over the same period (see Figure 4). The combined growth of HV traffic volumes was observed to have slightly decreased from 280,318 HVs in 2015 to 270,129 HVs in 2017, representing an approximately 4% decrease in HV volumes at the weighbridge stations. The HV volumes then steadily increased from 2017 to 2019 (385,664 HVs). This represented a 30% increase over the two years (2017 to 2019). Over the study period (2015 to 2019) the weighbridge stations experienced a 26% compounded increase in HV volumes. The compounded increase in HV volumes over
the study period could be a possible reason why a decreasing overloading trend (HV overloading normalised against HV volumes) was observed over the study period (see Figure 3 on page 15).

**Analysis of the HV axle classification and overloading trend**

The study identified various HV axle configurations on Namibian trunk roads, which include 1-1 (2-axle HVs), 1-2 (3-axle HVs), 1-1-1 (3-axle HVs), 1-1-2 (4-axle HVs), 1-1-3 (5-axle HVs), 1-2-2 (5-axle HVs), 1-2-3 (6-axle HVs), 1-2-2-1 (6-axle HVs), 1-2-2-2 (7-axle HVs) and 1-2-2-3 (8-axle HVs). The five most frequent HV axle configurations (axle configuration provided in Table 1) on Namibian roads between 2015 and 2019 were observed to be the 1-1, 1-2, 1-2-2, 1-2-3 and 1-2-2-2 axle configurations. Notably, it was observed that, while the average HV overloading trend slightly reduced from 2015 to 2019, the volumes of the 1-2-2-2 HV configurations (7-axle HVs) recorded an overall 25% increase over the study period, with 7-axle HV volumes ranging between 1 200 and 1 500 HVs per month over the study years. Several studies have found an increase in road damage due to an increase in overloaded higher axle configuration HVs over an extended period (Pinard 2010; Kandeke 2018). See Figure 5.

**Calculation of E80/ heavy vehicle (HV)**

Given the overloading magnitude observed, the study calculated E80/HV for different vehicles to establish whether they were within the recommended values (see Table 3) of the TRH 16 (Technical Recommendations for Highways) on traffic loading for pavement and rehabilitation design (CSRA 1991). The study found that the average E80/HV values for Namibia are lower than the recommended average TRH 16 values. The differences between the Namibian E80/HV values and the TRH 16 ranged from as high as 34% (Class 2) to as low as 10% (Class 7/Class 8) (see Table 3). In the context of road pavement design, this implies that roads in Namibia may be over/under-designed according to the TRH 16, which may considerably impact the service life of the road pavements.

**Impacts of overloading on structural design life (SDL) – road service life**

The study analysed the impact of heavy vehicle (HV) overloading on the service life (structural design life) of pavements using Equation 3, and the results are given in Figure 5. The study observed a varying degree of road service life for the roads serving the weighbridges due to HV axle overloading (see Figure 6), with the assumption that all trunk roads have a uniform design life of 25 years for Class B and Class C roads (CSRA 1996). The road serving the Walvis Bay weighbridge was estimated to have the highest reduced service life, i.e. from 25 years to 16 years. The roads serving the Katima Mulilo, Noordoewer, Aris, Rosh Pinah and Ariamsvlei weighbridges were also expected to exhibit declines of varying magnitudes in the service lives. The trunk routes using the Gobabis and Onhuno weighbridges were expected to have a service life above the assumed 25 years. Brakwater and Oshivelvo were excluded from the analysis due to insufficient structural design values. A study by Kiggundu and Lutombi (2004) noted that the average age of the Namibian bitumen road network, based on the date of the first upgrade, was 25.8 years. In comparison, the study observed an expected average road service life of 23.3 years with the HV overloading magnitude recorded and HV traffic volumes. The average expected road service life is below the design life (25 years) and the average age of the bitumen road network (25.8 years), as recorded in 2004.

**The effectiveness of existing overloading mitigations and enforcement measures**

One of the main reasons for premature failures and unsatisfactory performance of roads in Namibia is the overloading of heavy vehicles (HVVs) (Kandeke 2018). Road authorities need to protect roads from unnecessary damage and premature wear. Enforcement can help to eliminate overloaded HVs on the roads and can act as a deterrent by declaring that those travelling in disregard of laws and regulations would be apprehended or face effective punishment (Bagui et al 2013). The effectiveness of existing overload mitigation measures was evaluated by analysing the extent of HV overloading.

<table>
<thead>
<tr>
<th>HV class</th>
<th>TRH 16 (CSRA 1991) E80/HV</th>
<th>Average E80/HV for Namibia</th>
<th>Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 2 (2 axles)</td>
<td>0.30</td>
<td>1.10</td>
<td>0.70</td>
</tr>
<tr>
<td>Class 3 (3 axles)</td>
<td>0.80</td>
<td>2.60</td>
<td>1.70</td>
</tr>
<tr>
<td>Class 4 (4 axles)</td>
<td>0.80</td>
<td>3.00</td>
<td>1.80</td>
</tr>
<tr>
<td>Class 5 (5 axles)</td>
<td>1.00</td>
<td>3.00</td>
<td>2.20</td>
</tr>
<tr>
<td>Class 6 (6 axles)</td>
<td>1.60</td>
<td>5.20</td>
<td>3.50</td>
</tr>
<tr>
<td>Class 7/Class 8 (=&gt; 7 axles)</td>
<td>3.80</td>
<td>9.00</td>
<td>4.40</td>
</tr>
</tbody>
</table>
offences at the ten weighbridge stations over the study period (2015 to 2019). The study found that warnings for HV loading non-compliance were issued to 88.3% of offenders. The high number of warnings can be attributed to the 5% HV overloading tolerance provided for in the existing Road Traffic and Transport Act of 1999 (RTTA) (LAC 1999). It was also observed that 11.6% of offenders were either fined or prosecuted. This normally happens when overloading exceeds the 5% tolerance stated in the RTTA. Table 4 refers.

The RA 2015/2016 annual report worryingly notes that 93% of overloaded HVs were not fined for overloading (RA 2016). The study observed a gradual increase in the percentage of admission-of-guilt fines paid to the Namibian government (through lower courts and police stations) between 2015/2016 (31%) and 2019/2020 (61%) (see Table 5). The remaining fines have been converted to arrest warrants due to the failure/refusal of offenders to pay the fines (RA 2020). Some operators were reported to deliberately overload HVs due to the relatively low fines imposed on admission of guilt for loading non-compliance (Pinard 2010). In instances where the HV is overloaded to an extent where an admission of guilt cannot be imposed (HV overloading over 2 000 kg per axle), the operator is arrested and the vehicle is seized (Pinard 2010). Based on the above, Namibia needs to find innovative solutions to improve the effectiveness of the current mitigation measures to avoid HV operators taking advantage of the laws and regulations.

A study by Taylor et al (2000) found a general functional relationship between enforcement capability and overloading violation rates. This was based on several studies performed by seven state enforcement agencies in the United States. The findings observed a low overloading rate where there were high levels of overloading enforcement, resulting in an improvement in the service life of road infrastructure. Heavy vehicle (HV) overload control shortcomings identified

The study carried out interview questionnaires with weighbridge operators and users to investigate the effectiveness of HV overloading measures, and to identify shortcomings in existing strategies for curbing non-compliance. The results of the questionnaires are discussed below.

Weighbridge avoidance

The study found that weighbridge avoidance offences are a daily occurrence at most of the weighbridges in Namibia. Worryingly, the study found that 25% of the weighbridge stations experience weighbridge avoidance offences every hour. Respondents also mentioned that, due to the regular breakdown of the weighbridges, the drivers in some instances altogether avoid making the effort to go through the weighbridges for axle load measurements.

A study by Bagui et al (2013) noted that fixed overloading inspection stations restrict the flexibility of catching overloaded HVs. Thus, a combination of fixed and portable weighing systems (weigh-in-motion (WIM) systems) is necessary for more effective monitoring of weighbridge routes (Odula 2016; Bagui et al 2013). WIM systems are reported to greatly contribute to the monitoring of load bearing on the road infrastructure.
This paper presented a study investigating the magnitude of heavy vehicle (HV) overloading on selected Namibian trunk road classes (Class B and Class C roads), and an analysis of the effectiveness of existing strategies and measures in curbing non-compliance to axle loading. The findings of this study indicated that an average of 13% of the total HV traffic volumes on the selected road classes in Namibia were overloaded over the study period of 2015 to 2019.

Despite this, the study revealed a cumulative reduction of 2% in HV overloading from the year 2015 to 2019 (0.5% per year). The decrease is possibly attributed to the compounded increase in HV volumes rather than effective mitigation measures, which were found to be deficient. In comparison, previous studies by Pinard (2010), and Kiggundu and Lutombi (2004), had found an average rate of overloading between 20% and 29% respectively, between the years 2000 and 2010. Despite the cumulative reduction in the magnitude of overloaded HV traffic over the study period, the study revealed a reduced expected road service life. The reduction in the expected road service life can possibly be attributed to the observed overall increase in overloaded higher-axle configuration HVs (7-axle HVs) between 2015 and 2019. The average expected road service life over the study period was found to be 23.3 years, which is a reduction from the road service life of 25.8 years observed by Kiggundu and Lutombi (2004) in 2004.

The study also found that Namibia experiences lower E80 values compared to the values recommended by the TRH 16 on traffic loading for pavement and rehabilitation design (CSRA 1991). This finding is indicative of the differing traffic loading properties experienced in Namibia and South Africa. It is recommended that a study should be undertaken to aid with the investigation and adoption of a more localised pavement design approach for Namibian roads. This could help address the possible over- and under-design of pavements using equivalent single axle load (ESAL) recommendations that may not reflect the actual axle loading on the roads.

An evaluation of the HV overloading punitive measures that are in place found that between 31% and 61% of fines issued over the study period were paid directly to the Namibian government through local courts and police stations. The rest of the fines were converted to arrest warrants due to non-payment. The right to enforce these warrants/payments does not fall under the authority of Namibia. The study observed weighbridge stations operated by the Roads Authority (RA) of Namibia nor the Road Fund Administration (RFA) of Namibia despite being the custodian of roadway infrastructure. This provides a challenge in that these institutions are unable to ringfence the funds collected from HV overloading offences to maintain weighbridge infrastructure, improve mitigation measures, and address road pavement damage resulting from overloading.

This structural challenge also explains the lack of coordination between stakeholders, as observed by the questionnaire respondents, which has led to weighbridge equipment breakdowns and consequently a high rate of weighbridge avoidance offences by HV operators.

The study recommends an increase in HV overloading fines to fully recover the road pavement damage costs associated with axle loading non-compliance. For more effective use of HV overloading fines collected, the study recommends that fines be paid directly to the RA or RFA by incorporating them into the vehicle licensing and the Namibian Traffic Information System (eNaTIS).

The recommended revisions to the Namibian HV overload strategy (operation- and punitive measures) aim to address operational issues relating to overload control facilities, reduce non-compliance...
to axle loading regulations and reduce the deterioration of road pavements on the Namibian trunk road network.

DECLARATION OF INTEREST
None.

ACKNOWLEDGEMENTS
The authors would like to thank the Roads Authority of Namibia and the respondents to the questionnaires respectively for avail-
ing heavy vehicle traffic data and responding to questionnaires.

FUNDING
This study did not receive any specific grant from funding agencies in the public, commercial or not-for-profit sectors.

REFERENCES


A comparison of traditional road safety assessment methods and the newly developed ‘road safety deserts’ approach

M J W A Vanderschuren, A G Newlands

Road fatalities were labelled a pandemic as early as 1973 (BMJ 1973). The number of road fatalities reached 1.35 million in 2016. Currently over 3 500 people perish every day on the world’s roads. South Africa has one of the highest road fatality rates in the world, with a fatality rate of 25.9 deaths per 100 000 population (WHO 2018). In order to understand and improve the road safety situation of a region, effective road safety assessments must be carried out. This paper presents a comparison of four different road safety assessment approaches, both traditional and novel, and serves as a proof of concept for the ‘road safety desert’ methodology, a new technique adapted from the ‘transit desert’ concept. This new approach to road safety assessment explores the possibility of geo-coded supply and demand comparisons to identify ‘road safety deserts’ – areas that have a comparatively higher road safety risk. This paper shows that there are several unique and effective ways to assess road safety, and that each approach incorporates different characteristics within their methodologies. It is recommended that road safety analysis is conducted using a multitude of methods, so as to improve understanding and intervention selection.

Keywords: road fatalities, deserts, road safety deserts, road infrastructure, Cape Town

INTRODUCTION

“Road traffic deaths upend countless lives and cost countries around 3% of GDP each year,” notes Dr Etienne Krug, Director of the Department for Social Determinants of Health, of the World Health Organisation (WHO). “This is an unacceptable price to pay for mobility. Putting safety at the heart of our mobility systems is an urgent health, economic, and moral imperative” (WHO 2022). Although road fatalities were labelled a pandemic as early as 1973 (BMJ 1973), fatalities have continued to climb, reaching a staggering 1.35 million in 2016. “The data shows that low- and middle-income countries bear the greatest burden of road traffic fatalities and injuries” (WHO 2018). Currently, over 3 500 people perish every day on the world’s roads.

While many developing nations have been successful in reducing the number of road fatalities, the pandemic persists in Africa. Based on data released by the WHO in 2013 (WHO 2013), Vanderschuren and Zuidgeest (2017) determined that the average fatality rate in Africa is 24.1 fatalities per 100 000 population, which is substantially higher than the global fatality rate of only 17.0 fatalities per 100 000 population. Between 2010 (WHO 2013; Vanderschuren & Zuidgeest 2017) and 2016 (WHO 2018), road fatality rates in South Africa have reduced from 31.9 fatalities per 100 000 population to 25.9 fatalities per 100 000 population. Although this is a significant reduction, the rate of decrease is not nearly enough to meet the global and South African target of –50% fatalities in absolute terms between 2010 and 2020 (WHO 2018). Based on the latest Road Traffic Management Corporation (RTMC) data (RTMC 2022), the current fatality rate is approximately 20.5 fatalities per 100 000 population. This is mainly due to a continuing growth in population and stabilising absolute fatality rates.
According to the WHO (2018), 29% of all fatalities worldwide are car occupants, 28% motorised two- and three-wheelers, and 26% pedestrians. A total of 44% of all fatalities in the African region are pedestrians and cyclists, i.e. the most vulnerable road users. The second-largest group of fatalities in Africa are car occupants (40%), making it the region with the second-highest driver and passenger fatality rate (WHO 2018). The large number of (informal) public transport services on Africa’s roads make a significant contribution to these values. The burden of road-related fatalities is very high in these low- and middle-income countries, as they have 93% of the world’s fatalities and only 60% of the world’s vehicles (WHO 2018). Given the growth in vehicle population, there is a likelihood that road fatalities on the African continent will continue to grow.

In order to understand and improve the road safety situation of a region, and thus decrease the number of road traffic crashes and fatalities through appropriate interventions, effective road safety assessments must be carried out. This paper investigates and discusses four approaches to assessing the state of road safety in an area. This paper also serves as a proof of concept for the ‘road safety desert’ methodology, a new analysis technique adapted from the ‘transit desert’ concept. From a transport justice point of view, this new approach to road safety assessment explores the possibility of using supply and demand comparisons per geographical area to identify ‘road safety deserts’ – areas that have a comparatively higher road safety risk than other areas.

METHODOLOGY

Based on a literature review and available data, a comparison of four different road safety assessment approaches was completed (see Figure 1). These four approaches are hotspot analysis, fatality rates, fatalities per mode share, and ‘road safety deserts’, a novel theory detailed in this study.

A literature review, including the authors’ previous work, was conducted for the first three approaches to identify their key characteristics and calculation steps, and an example of a previous application of each approach was detailed. For the fourth approach, literature on earlier ‘desert’ theories (‘food deserts’ and ‘transit deserts’) was reviewed to inform the development of the ‘road safety desert’ theory and calculation process.

Based on data availability, specifically geo-coded information regarding road fatalities, the chosen case city for this research was Cape Town. Cape Town is the largest city in the Western Cape Province, and the second-largest metropolitan area, by population size, in South Africa (CoCT 2015a). The city continues to expand
rapidly, with the population estimated to grow from 4 758 433 inhabitants in 2021 to 5 133 369 inhabitants in 2025 (Western Cape Government 2021). Cape Town has an average density of 1 915 persons/km², which is relatively low compared to other major cities (Western Cape Government 2021). This density varies significantly within certain suburbs of Cape Town, with more affluent areas having much lower densities than poorer areas (Vanderschuren et al 2022).

In this study, the City of Cape Town (CoCT) was separated into 16 transport analysis zones (TAZs), which are the smallest geographical areas used for city-wide travel demand model forecasting (see Figure 2 on page 21).

Road fatality data was sourced from the CoCT Forensic Pathology Laboratory (FPS) database and the Integrated Provincial Analysis System (iPAS) for 2011 – 2015 (CoCT 2015b). Data from the 2013 National Household Travel Survey (NHTS) was used to determine mode share and population counts (StatsSA 2013). The ‘road safety desert’ approach in this paper assesses road safety with respect to motorised and non-motorised transport.

The calculation process for each approach is detailed and applied to the case city, Cape Town. A comparison is then made between the four approaches, which is discussed further, followed by conclusions and recommendations.

HOTSPOT ANALYSIS

Background
A hotspot (or black spot) is a “location that has a higher expected number of crashes than similar locations, as a result of local risk factors” (TRACECA 2015). Hotspot analysis is an approach to road safety assessment that identifies these hazardous locations and enables targeted infrastructure implementations to be carried out to improve the safety of each location.

The definition of a hotspot differs internationally. For example, in Norway a hotspot is defined as any location, 100 m long, where a minimum of four crashes resulting in injuries have occurred during the past five years. In Switzerland, a hotspot on a motorway is any site (up to 500 m long) that has recorded a minimum of ten crashes, four injuries, and two fatalities within the last two years (Elvik 2008). These international classifications cannot be transferred directly to the South African context, as the state of road safety in South Africa is much worse. For example, Vanderschuren et al (2017a) found one location in Cape Town where 618 crashes occurred within a 100 m² area in one year, while Gregory and Jarret (1994), in a study done in England, defined an area as a high-risk site if only 20 crashes were recorded over three years on a 100 m length of road. This illustrates that the road safety problem is much more severe in South Africa, and therefore an appropriate classification of hotspots needs to be defined for this context.

Hotspot application for the case of Cape Town
In 2017, a hotspot analysis was conducted for Cape Town (Vanderschuren et al 2017a). Geo-coded fatality data from iPAS and the CoCT’s FPS database for 2015 was used in this analysis. This led to the use of the ‘fishnet’ tool in GIS, which clusters fatalities that occurred at the same location, i.e. hazardous locations or hotspots. The area size used was 100 m by 100 m, in accordance with international best practice (Elvik...
2007). This was verified for the South African context via Google Earth where a typical South African intersection size was found to be approximately 100 m². This area size, therefore, reduces the chance of links in the road network being included/combined with the intersection area. As crossing traffic represents conflicts that could potentially lead to road crashes and fatalities, the authors wanted to ensure that intersections could be identified (Vanderschuren et al 2017a).

Fatality locations were plotted on a map of Cape Town, and a preliminary analysis of this map found that many fatalities occurred in the same location. It is important to note that the city questioned the accuracy of the location data. The authors are not in a position to verify the accuracy. While the authors (Vanderschuren et al 2017a) recommended that the accuracy of geo-location data be improved for practical application in South Africa, the method is conceptually sound and proven in multiple locations around the world.

For completeness, Figure 3 shows the top ten hazardous locations in Cape Town based on the 100 m × 100 m ‘fishnet’ tool approach. Fatalities were ranked into hotspots, listing the areas with the most fatalities in one year (in this case, the year 2015).

**FATALITY RATES**

**Background**

Absolute fatality numbers, while being useful for locating hotspots and implementing targeted interventions, do not allow for accurate comparisons of road safety across different regions with different populations and vehicle numbers. Fatality rates, such as fatalities per 100 000 population, crashes per 10 000 vehicles, and crashes per vehicle kilometres travelled, allow for this cross-regional comparison to occur. Road fatality rates per 100 000 population are commonly used by the WHO, who defines a road traffic fatality as “any person killed immediately or dying within 30 days as a result of a road traffic accident” (WHO 2013). While this definition is also used in South Africa, the total number of fatalities recorded may not be completely aligned with this definition. This is partly due to the fact that fatalities that occur days after a road traffic accident (and not immediately at the scene of the crash) are often not recorded as a road traffic fatality, due to poor feedback processes between the police and hospitals.

**Fatality rate application for the case of Cape Town**

A study completed by Vanderschuren et al (2017a) used road fatalities per 100 000 population to assess the state of road safety in Cape Town, using transport analysis zones (TAZs) as the geographical areas to be assessed (see Figure 2). Total fatality data, obtained from CoCT’s FPS for 2011 – 2015 (CoCT 2015b), was converted to average annual fatalities per 100 000 population per mode for each TAZ (see Figure 4 where the pie chart size indicates the total number of fatalities). The reader should note that, while the FPS data should be closely aligned to the definition of a road fatality, as defined by the WHO (2013), there is no guarantee. The authors, therefore, caution regarding direct comparison of the WHO and local fatality rates.

An interesting finding of the study by Vanderschuren et al (2017b) was the significant differences between absolute fatalities per TAZ, compared to the fatality rates per 100 000 population. This is illustrated in Figure 5. Without going into too much detail regarding the results, it is very clear that the TAZ that needs intervention based on absolute fatalities (Mitchells Plain, which is a high-density suburb) differs from the TAZ based on fatality rates per 100 000 population (Durbanville, a suburb with some major mobility corridors...
that are less congested and, therefore, have higher speeds and, hence, more fatalities, than mobility corridors closer to the CBD of Cape Town).

**FATALITIES PER MODE SHARE**

**Background**

Fatality rates (per mode) cannot be expected to be homogeneous across a TAZ or road category. For example, in the European setting, where conducing secondary and tertiary road networks are available, pedestrian fatalities on freeways hardly occur. This is because the mode (pedestrian) is absent in this environment. Based on this insight, it is likely that road fatalities are related to the mode share in an area. This is investigated in this section.

**Fatalities per mode share application for the case of Cape Town**

Vanderschuren et al. (2017a) combined the analysis of mode distribution per TAZ and fatalities to calculate fatalities per mode share. The percentage difference between mode distribution and absolute fatalities ($Y$) is used. The percentage mode share was subtracted from the percentage of fatalities for that mode to generate a delta value.

$$Y = \frac{F_m * 100}{\Sigma Fa} - \frac{T_m * 100}{\Sigma Ta}$$

(1)

Where:

- $F_m$ = absolute fatalities
- $T_m$ = trips per mode.

Figure 6 shows the results for the various modes. In this method, “... a positive difference indicates that the percentage death toll for the road user type is higher (unwanted) when compared to the percentage of the population that utilises that particular mode, for their daily trips and vice versa ...” (Vanderschuren et al. 2017a:18).

**THE ‘DESERT’ APPROACH**

**Background**

Over the past three decades, the equitable distribution of goods and services has been assessed via the ‘desert’ concept. In the academic literature, ‘desert’ is based on a comparison of supply and demand, while correcting for the area size (Clarke et al. 2002; Whelan et al. 2002; Wrigley et al. 2002; Ver Ploeg et al. 2011).

The ‘food desert’ concept started in the early 1990s, when a resident in the United Kingdom (UK) used the term ‘food desert’ for the first time. In 1995, the term was first adopted by the UK government (Beaumont et al. 1995). Food deserts are characterised by areas where residents that do not have access to private cars or who are unable to access/afford public transport, are forced to shop at corner shops where prices are high and fresh produce is scarce, as opposed to more affordable supermarkets with healthy produce that are usually further away (Ver Ploeg et al. 2011; Jiao & Dillivan 2013).

In the field of transport, the desert theory was first applied by David Hulchanski of the University of Toronto, who investigated ‘transit deserts’ in his Three Cities report (Hulchanski 2010). Jiao and Dillivan (2013) and Jiao (2017) refined the transit desert theory and defined “areas that lack adequate public transit service, given its contained population that is deemed transit dependent”. The aim of the food desert methodology can be reworded to describe the aim of the transit desert methodology, namely “to achieve equitable access to high-quality, affordable public transport for everyone” (Newlands 2020). Vanderschuren et al. (2021) then transferred and applied the transit desert theory to the South African context, proving that the methodology can be adapted and applied in different contexts, including cities in the global south.

This paper uses the knowledge gained by the authors regarding ‘transit deserts’ and adapts the theory to the field of road safety, investigating the possibility of using supply and demand comparisons per geographical area, with the aim to identify ‘road safety deserts’. This ‘road safety desert’ methodology is useful in assessing the state of road safety in an area through the lens of justice, as it compares areas within the same region to each other, enabling the determination of the risk level of an area compared to the region’s average.

As the application of ‘road safety deserts’ is novel, this section includes a more elaborate description of the calculations. For the previous sections, readers can refer to the literature for further calculation details.

**Safety value calculation**

The equations used to calculate the safety value per TAZ are provided in Equations 2, 3 and 4. Firstly, the demand for transport is calculated. This study utilises the available trips as per the National Household Travel Survey (NHTS) (StatsSA 2013). The demand ($D$) is determined by comparing the number of trips ($T_{ma}$) to all trips ($T_{a}$) in a TAZ. In a similar way, the safety ($S$), based on iPAS data, is calculated by dividing fatalities per mode ($F_{ma}$) by the total number of fatalities ($F_{a}$) in a TAZ. The final safety value ($B$) is determined by subtracting safety ($S$) from demand ($D$).
\[ D = \frac{\sum T_{m}}{\sum T_{a}} \]  
\[ S = \frac{\sum F_{m}}{\sum F_{a}} \]  
\[ B = D - S \]

Supply quality value calculation

The supply quality value is calculated using infrastructure-related information in the iPAS system and is an indication of the overall road quality in each TAZ. The following attributes are included: built-up area \((X_1)\); junctions \((X_2)\); street lighting \((X_3)\); obstructions \((X_4)\); road alignment \((X_5)\); road marking type \((X_6)\) and condition \((X_7)\); road sign condition \((X_8)\); road surface type \((X_9)\), quality \((X_{10})\) and condition \((X_{11})\); cross-section characteristics \((X_{13})\) and speed \((X_{14})\). All supply quality attributes are currently included in a binary manner. For example, dry road conditions are assumed to be superior (positive) to all other road surface conditions (wet/water, loose gravel/sand, ice, snow, slippery). As for demand, the portion of good road supply is calculated.

This paper currently does not include characteristics related to traffic signals, as research on this attribute is still under way. The equation used to calculate the supply quality value per TAZ is provided in Equation 5. The overall supply quality value \((Q)\) is the sum of all attributes \((X_n)\), where the total positive cases \((\sum X_{np})\) is divided by all cases \((\sum X_{na})\).

\[ Q = \frac{\sum X_{1p}}{\sum X_{1a}} + \frac{\sum X_{2p}}{\sum X_{2a}} + \ldots \]  

Overall safety desert value calculation

The Z-value calculation can begin once the results for safety \((B)\) and supply quality \((Q)\) have been determined.
The safety and supply quality values are converted into Z-values to standardise the criteria. The Z-value indicates how many standard deviations ($\sigma$) a TAZ is from the mean (average of all TAZs). In other words, a Z-value is a numerical measurement, used in statistics, where the value ($x$) is compared to the average of a group ($\mu$). If a Z-value is 0, it indicates that the data point is identical to the mean value (Heyes 2019) (see Equation 6).

$$Z = \frac{x - \mu}{\sigma} \quad (6)$$

The next step is to subtract the safety values from the supply quality values to calculate the overall safety desert Z-value ($OZ$) for each TAZ (see Equation 7).

$$OZ = Qz - Bz \quad (7)$$

In this study, a positive overall safety desert value indicates that there is a lower road safety risk than the risk for the average Capetonian (group value). A negative final Z-value, on the other hand, reflects a less safe environment, i.e. a higher road safety risk. This methodology is similar to the way ‘transit deserts’ were identified in the literature but has been adapted to suit the field of road safety (Hulchanski 2010; Jiao & Dillivan 2013; Jiao 2017; Vanderschuren et al 2021).

‘Road safety desert’ application for the case of Cape Town
For the case study using Cape Town, the identification of ‘road safety deserts’ was done by subtracting the safety Z-values ($Bz$) from the supply quality Z-values ($Qz$), applying the methodology described in the previous section. Analysis zones with a higher overall road safety risk had Z-values below zero, and a ‘road safety desert’ was classified as a zone with a Z-value below negative two.

Figure 7 (motorised transport) and Figure 8 (non-motorised transport) show the Z-values for all TAZs in Cape Town, for supply quality ($Qz$), safety ($-Bz$) and the overall ($OZ$) safety desert values. To make it easier for the reader to understand the information displayed, the authors display the negative safety ($-Bz$) in the remainder of this paper.

As space is limited, only the results for motorised transport (Figure 7) will be discussed. The results for non-motorised transport (Figure 8) can be interpreted similarly. Ten TAZs (63% of zones analysed) in Cape Town were classified as having a higher overall road safety risk. Half of these zones have overall Z-values below negative one, which indicates a significantly high overall safety risk (see Figure 7c). No TAZ was identified as a ‘road safety desert’, as none of the Z-values are below negative two. However, one area (the Northern Corridor) has a value of –1.93 and is very close to being identified as a ‘road safety desert’.

Analysis zones with a lower overall road safety risk had Z-values above zero, and a road safety ‘utopia’ was classified as a zone with a Z-value above positive two. Figure 7c also shows the TAZs in Cape Town with a low overall road safety risk, when compared to the other TAZs. Six TAZs (37% of zones analysed) were classified as having a lower overall road safety risk (Figure 7c). Four of these zones had overall Z-values above one, which indicates a significantly low overall safety risk.

DISCUSSION
This paper describes various road safety assessment tools that can be used to reduce the road safety burden in South Africa and beyond. Some tools use absolute fatalities as an output to assess the situation, while others convert the information to fatality rates, either per 100 000 population or per land area. Numerous literature items and tools argue that fatalities need to be analysed per mode, to improve the identification of measures. In the case of the ‘road safety desert’ theory, social justice and infrastructure characteristics are included in the methodology. Table 1 provides an overview of the characteristics included in the described road safety approaches.

All methods are based on absolute fatality rates. In the case of hotspots, these

![Figure 7](image_url)
absolutely numbers are used to identify locations that require road safety interventions, for example infrastructure improvements. While not demonstrated in this paper, hotspot analysis can be conducted per mode.

Fatalities rates, as defined by the WHO (2013), convert absolute fatalities into rates per 100 000 population. In some cases, this is done for the various modes of transport, although this was not demonstrated in this paper. Displaying fatalities rates per geographical areas does bring in a social justice component.

Fatalities per mode share is not a common tool. Although already applied in 2017, this approach has not been followed internationally. If applied per location (TAZ), the fatalities per mode provide a social justice aspect. In this paper the fatalities for drivers, passengers, pedestrians and cyclists are displayed, indicating which TAZ has an over- or under-representation of fatalities.

In this study, ‘road safety deserts’ have been established for the first time. The theory development is based on earlier work related to ‘food deserts’ (Clarke et al 2002; Whelan et al 2002; Wrigley et al 2002) and ‘transit deserts’ as described by Hulchanski (2010), Jiao and Dillivan (2013), Jiao (2017) and Vanderschuren et al (2021). Social justice is at the core of the methodology, while land area and infrastructure are part of the approach. Although not displayed in this paper, the method can be conducted for various modes. The paper includes motorised and non-motorised transport as an example.

The four approaches described in this paper each have a unique method in identifying locations where interventions

### Table 1 Comparison of road safety approaches

<table>
<thead>
<tr>
<th>Indicators</th>
<th>Hotspots</th>
<th>Fatality rates</th>
<th>Fatalities / mode share</th>
<th>Road safety deserts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute fatality input</td>
<td>Main feature of the method; fatalities must be geo-coded</td>
<td>Fatalities are included related to population size</td>
<td>Fatalities per mode are included as a percentage of all fatalities</td>
<td>Fatalities are included per mode</td>
</tr>
<tr>
<td>Absolute fatality output</td>
<td>Absolute numbers are displayed geographically</td>
<td>Not included</td>
<td>Not included</td>
<td>Not included</td>
</tr>
<tr>
<td>Per 100 000 population</td>
<td>Not included</td>
<td>Main feature of the method</td>
<td>Not included</td>
<td>Not included</td>
</tr>
<tr>
<td>Land area</td>
<td>Not included</td>
<td>Not included</td>
<td>Not included</td>
<td>Main feature based on transport analysis zones (TAZs)</td>
</tr>
<tr>
<td>Modes</td>
<td>Geographical depiction can be provided per mode</td>
<td>Can be calculated but is not intrinsic to the method</td>
<td>Useful to use this method per mode choice</td>
<td>Useful to use this method per mode choice</td>
</tr>
<tr>
<td>Infrastructure characteristics</td>
<td>Not included</td>
<td>Not included</td>
<td>Not included</td>
<td>Main feature of the method</td>
</tr>
<tr>
<td>Social justice</td>
<td>Not included</td>
<td>Becomes a social justice indicator if various geographical areas are compared</td>
<td>Becomes a social justice indicator if various geographical areas are compared</td>
<td>Main feature of the method</td>
</tr>
</tbody>
</table>
are needed to reduce road fatalities. No approach is superior to another, and each approach results in valuable information about the road safety status quo of an area.

CONCLUSIONS AND RECOMMENDATIONS

This paper presents a comparison of four different road safety assessment approaches, i.e. three traditional approaches and the novel ‘road safety deserts’ approach. The methodologies of these four approaches have been discussed and applied to the City of Cape Town as an example of how they are used. The methodologies were then compared with one another, looking at characteristics such as land area, modes, social justice and infrastructure characteristics. The ‘road safety desert’ methodology includes more indicators. However, the traditional methods also have their place. The authors conclude that applying multiple methods increases the opportunities to combat road fatalities. Each of the included methods have a role to play.

The ‘road safety desert’ methodology is a new road safety assessment approach introduced in this paper. Both calculations in this methodology – safety and supply quality values – need further validation and fine-tuning. Vanderschuren et al (2021) identified that “the use of large TAZs hinders the development of detailed transit supply action plans”. This study, similarly, uses large TAZs, due to data limitations. As smaller analysis zones are more conducive to the identification of detailed action plans, it is recommended that disaggregated transport information generated in the South African context be identified. From a road safety perspective, geographical coordinates would be optimal. It is, therefore, recommended that future applications of this methodology make use of smaller analysis zones to improve the accuracy of the results.

Additionally, the safety and supply quality calculations could differ, depending on the mode. For example, the current road supply quality characteristics are appropriate for assessing motorised transport, specifically. When performing the ‘road safety desert’ analysis for pedestrians, certain supply characteristics, such as the number of pedestrian crossings or the length of pedestrian walkways, should be included so that the supply quality value is accurate for that mode. In the current raw data, this information is not available. It is recommended that municipal asset registers, as well as the road safety database, add such information.

It must also be mentioned that safety value calculations in the ‘road safety desert’ method are based on trip-making by residents. Trips in practice go across TAZs, as the origin and destination of trips are not necessarily in the same TAZ. However, this is also the case regarding ‘food desert’ (Beaumont et al 1995; Clarke et al 2002; Whelan et al 2002; Wrigley et al 2002; Ver Poel et al 2011) and ‘transit desert’ (Hulchanski 2010; Jiao & Dillivan 2013; Jiao 2017; Vanderschuren et al 2021) calculations, as reported by various authors. The authors of this paper acknowledge that, in the case of tourists, events or other attractions, the use of resident-based mode share may hamper the accuracy of the calculations. In these cases, traffic counts that include drivers, passengers and pedestrians are recommended.

Within the ‘road safety desert’ approach, this paper uses the term ‘utopia’ for areas that demonstrate a much lower road safety risk than the risk for the average Capetonian. Although from a local context this terminology may be appropriate, the authors feel strongly that ‘utopia’ is only achieved once all road fatalities are eliminated globally.

Overall, this paper shows that there are several unique and effective ways to assess road safety and that each approach incorporates different characteristics within their methodologies. It is therefore recommended that road safety analysis is conducted using a multitude of methods, including hotspot analysis, fatality rates, and fatalities per mode share, as well as ‘road safety deserts’, mining the data to such an extent that an improved understanding is gained. This will lead to the best possible improvement approach.

ACKNOWLEDGEMENTS

The authors would like to thank Mr Robert Cameron for his work on applying the transit desert methodology to South Africa, and would like to acknowledge the Western Cape Road Safety Study completed in 2017 by Vanderschuren et al for its work on mode share and fatalities. Additionally, the authors would like to thank the Western Cape Government for access to the geocoded road safety data via the Provincial Analysis System (iPAS). This work is based on research supported by the National Research Foundation of South Africa and the Council of Scientific and Industrial research (Grant Number 138142).

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Western Cape Government. iPAS (Provincial Analysis System). Various years.


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