Methodology for Functional Design of Low-Level River Crossings in South Africa

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With the renewed emphasis on low-volume roads in South Africa, the use of low-level river crossings (LLRC) will receive increased attention in the future. To evaluate low-level river crossings, it is necessary to know how often certain floods will occur and how long the structure can be expected to be submerged. From a functional design point of view, no guidelines exist on the size of openings required on an LLRC. The aim of the study is to quantify the extent of overtopping and provide a functional design method for the selection of LLRCs. The methodology is based on an analysis of historic river flow data obtained from the Department of Water Affairs of South Africa. Data were collected on several catchment areas with a variety of characteristics for a 20-year period. The 1-in-2-year flood was then determined for each catchment area. Considering various fractions of the 1-in-2-year flow, the number of times this flow as exceeded and the duration of excess flow were determined. This information was used as a basis for developing models to quantify the extent of overtopping. Based on these models, three levels of design were defined; namely 0.25, 0.5, and 1.0 times the 1-in-2-year flood. It was accepted that apart from passing under the structure, the design flood also may partially be accommodated over the structure. The acceptable flow depth for subcritical and supercritical flow during which a vehicle can pass over the structure was determined.

Since the first democratic elections in the history of South Africa in April 1994, policy makers have begun to focus more attention on the extensive disadvantaged rural areas of the country. The Reconstruction and Development Programme (RDP) (*1*) outlines the policies of the new government in this regard. In the transportation sector, low-volume roads are expected to play an increasingly important role in these areas. With renewed emphasis on low-volume roads, the use of low-level river crossings (LLRC) will also receive increased attention in the future. An LLRC, or low-water crossing, is a road-stream crossing designed to allow flooding during periods of high annual runoff (*2*). Compared with conventional high-level bridges, LLRCs are considered appropriate for tertiary roads mainly because of their low cost. These structures range from concrete slabs and causeways to submersible span structures. Eriksson (*2*) provides guidelines on structure type selection. During the development of South Africa's road network from the 1930s to 1950s, many of the main roads were constructed with these types of structures. After this initial development, high-level structures were generally used.

To evaluate LLRCs, it is necessary to know how often certain floods will occur and how long the structure is expected to be submerged. This information is needed to evaluate the impact on road users, who must use alternative routes while the structure is flooded or wait for the structure to become passable again. Without this information, an economic analysis of the investment decision required for the development of an LLRC is not possible.

From a functional design point of view, no guidelines exist on the size of openings required on an LLRC. Although some engineers design for the 1-in-2-year flood, others believe this is excessive, particularly for large catchment areas, relatively dry areas, or low-order roads where even unvented causeways may be acceptable.

The aim of the study is to quantify the extent of overtopping and provide a design method for the selection of LLRCs. The development of three models to describe the flooding of LLRCs and a design methodology are presented. The study is based on research that forms part of the research project, *Guidelines on Project Evaluation for Tertiary Roads* (*3*), done on behalf of the South African Roads Board.

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METHODOLOGY

The Department of Water Affairs of South Africa monitors river flow at several hydrological gauging stations throughout the country (*4*). Historic river flow data for the period August 1, 1972 to July 31, 1991 were obtained from the department for a number of catchment areas with a variety of characteristics. The flood with a 2-year recurrence interval was determined for each catchment area, using the rational, unit hygrograph, and two empirical methods (*5,6*). The number of times flow was exceeded and the duration of excess flow were then determined for various fractions of the 1-in-2-year flood.

This information was used as a basis for the models to be developed. Based on these models, three levels of design were defined; namely 0.25, 0.5, and 1.0 times the 1-in-2-year flood.

Besides passing under the structure, the design flood also may partially be accommodated over the structure provided that vehicles can still pass over the structure. The acceptable flow depth for subcritical and supercritical flow under which a vehicle can pass over the structure was determined.

DATA COLLECTED

The study area includes drainage regions A, B, and X (*4*), shown in Figure 1. This area is in the northern part of the country and may be described as that part of the country north of an imaginary east-west line drawn through Johannesburg. After the methodology has been established, the study area may be extended to the whole of South Africa.

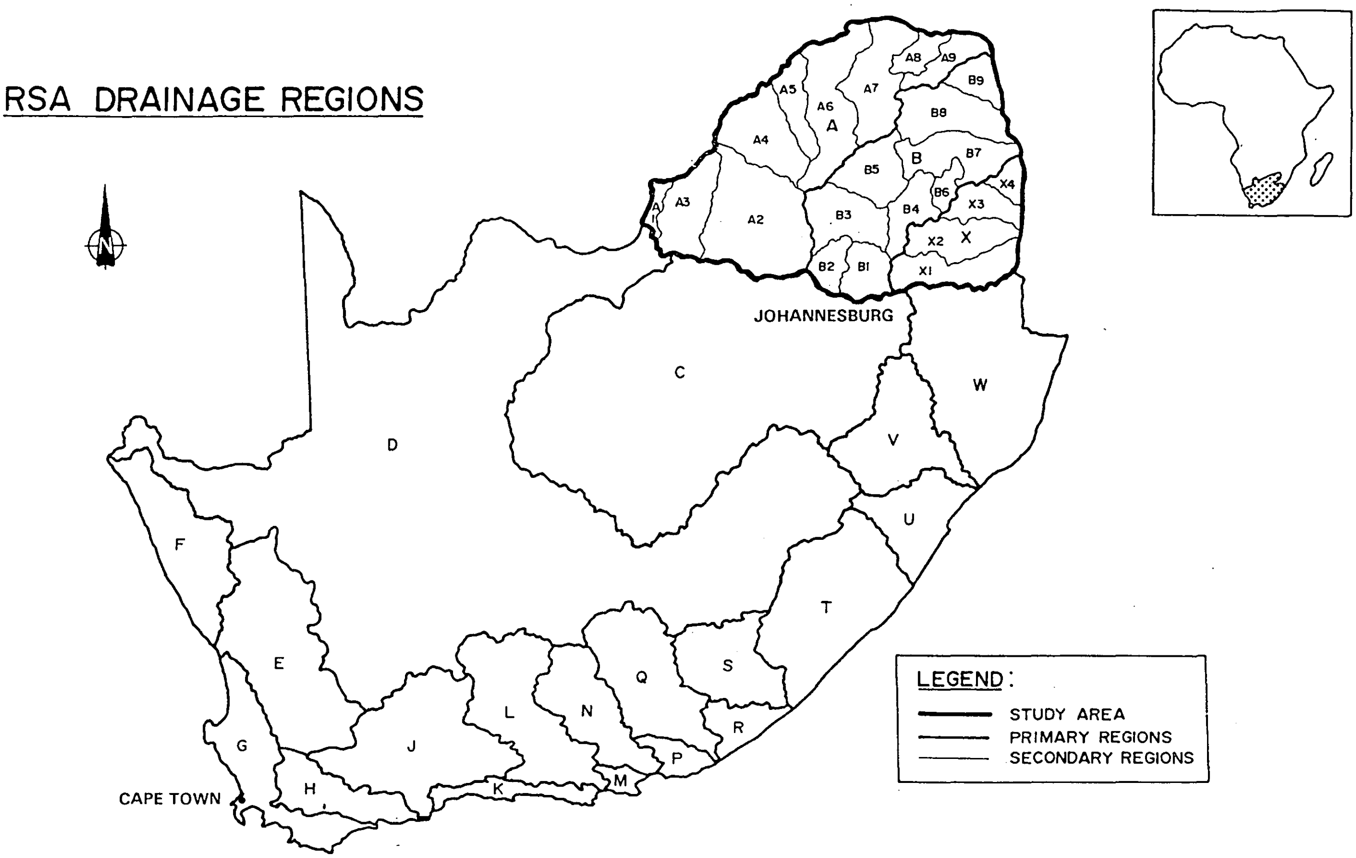


FIGURE 1 Study area.

The following criteria were used for the selection of gauging stations:

- In the development of the methodology, it was decided to focus on a limited number of drainage regions. Drainage regions A, B, and X were chosen because those areas are composed of mountainous, rolling, and flat terrain, and rainfall varies from 320 to 1,300 mm per year. Territories such as Lebowa, Venda, Gazankulu, Kwandebele, and large portions of Kangwane and Bophuthatswana (all former homelands where the need for the provision of low-level structures is high) are also in the area.
- Based on experience with low-level structures catchment areas were grouped as follows: less than 100 km^2, between 100 km^2 and 500 km^2, and between 500 km^2 and 1,200 km^2. In the case of catchment areas greater than 1,200 km^2 a detailed analysis was performed instead of using a generalized model as discussed in this study.
- Only gauging stations with complete or almost complete data for the past 20 years were considered.
- Only gauging stations serving rural catchment areas were considered.

RESULTS

Each gauging station has a gauging weir, which measures the river flow on a continuous basis. A range of five flow values, expressed as a fraction of the 1-in-2-year flood, was selected for each gauging station. The range chosen depended on the capacity of the gauging station; for example, if the capacity was 1.4 times the 1-in-2-year flood, the range 0.25, 0.50, 0.75, 1.00, 1.25 was used. If the capacity was only 0.6 times the 1-in-2-year flood, the range 0.1, 0.2, 0.3, 0.4, 0.5 was used. For each of these flow values an analysis of the flow data was made to determine

- The total time period per year that the flow value was exceeded,
- The number of times per year that the flow value was exceeded, and
- The average duration flow was exceeded.

Two curves were then developed for each of the preceding characteristics: one serving as an envelope and one representing the mean values. Of the various relationships that were tested, the following was found to fit the data best:

$$Y = aX^b \tag{1}$$

where Y and X are as shown in Table 1 and a and b are regression coefficients.

The data and the curves fitted are shown in Figures 2, 3, and 4. The values of the regression coefficients for the various cases are provided in Table 1.

TABLE 1 Value of Calibration Constants

DESCRIPTION		AVERAGE CURVE		ENVELOPE CURVE	
Y	X	a	b	a	b
Time exceeded per year (hrs)	Fraction of Q_2*	2.58	-1.38	12.00	-1.30
Number of times exceeded/year	Fraction of Q_2*	0.47	-0.74	1.40	-0.80
Average duration of excess flow (hrs)	Fraction of Q_2*	3.41	-0.70	6.00	-1.15

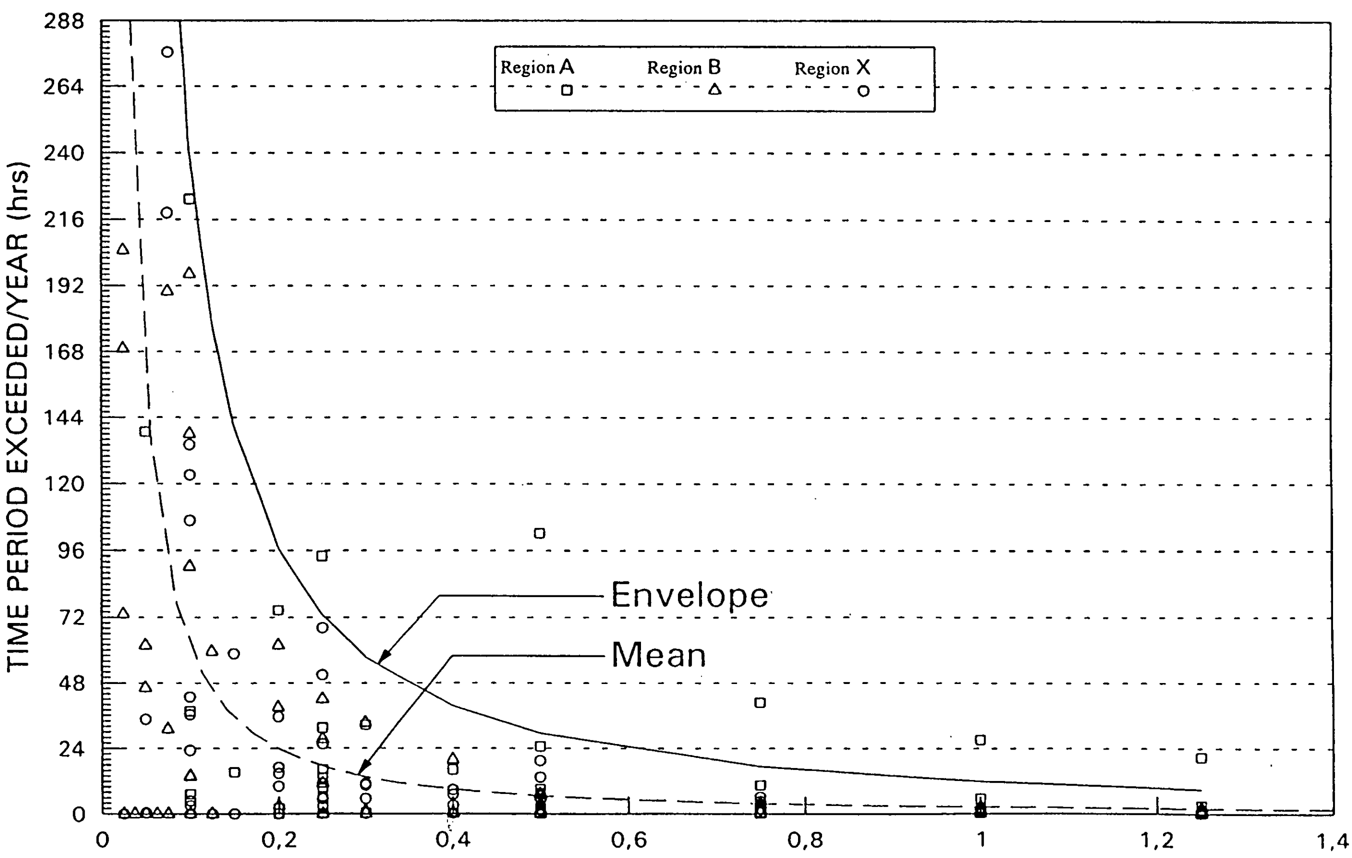
* Q_2 is the 1 in 2 year flood

DESIGN METHOD

After the models predicting the number of times certain flows will be exceeded and the duration of these flows were available, the design method was developed.

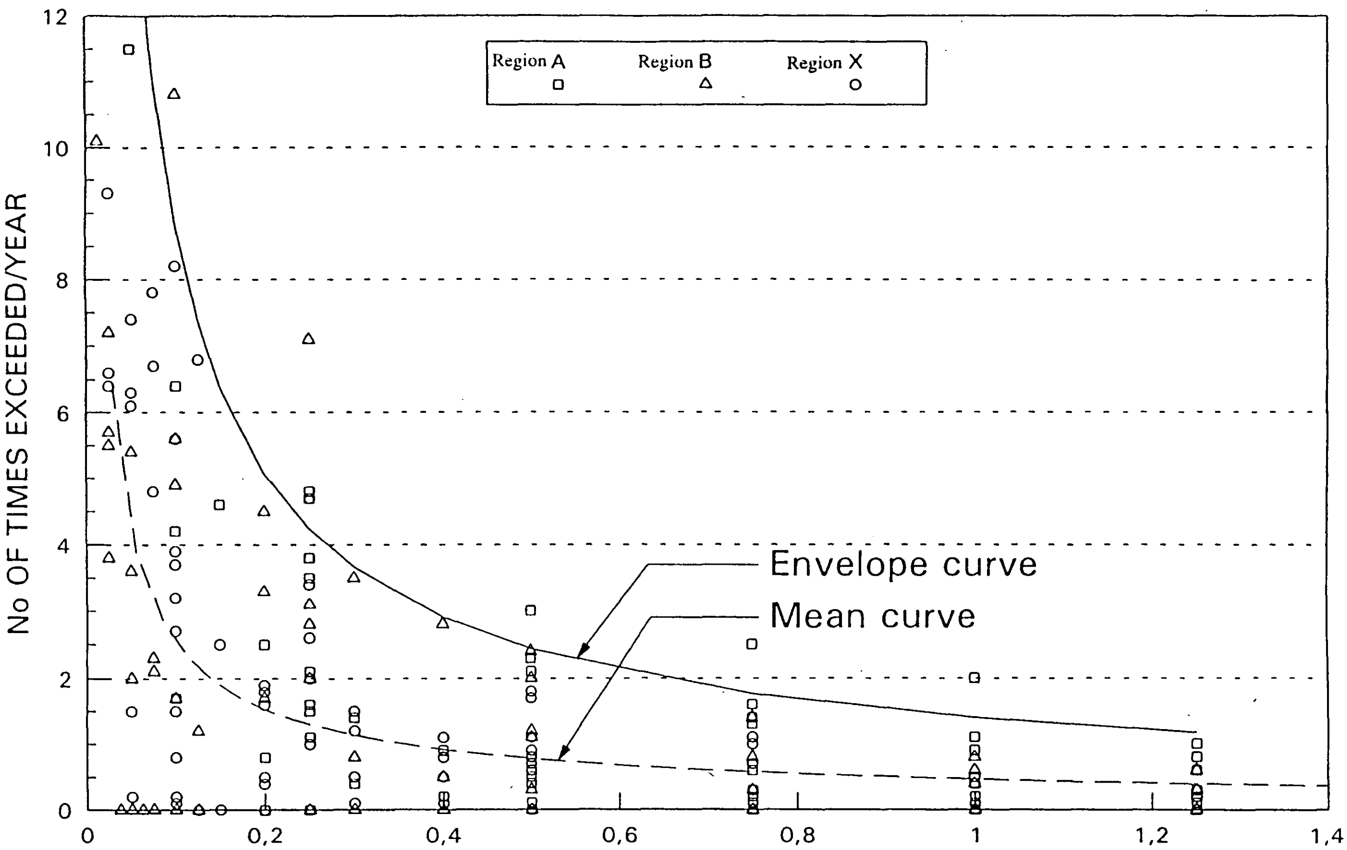
First, the design level (which provides an indication of the level of service to be expected from the structure) is chosen. Three design levels were defined, as shown in Table 2. If Design Level 1 is used, the design flow will be exceeded 1.3 times per year on average and the average flood duration will be 9 hr (as shown in Table 2, these values were as high as 4.2 times per year and 30 hr per flood for some of the gauging stations). If Design Level 3 is chosen, the design flow will be exceeded only 0.5 times per year on average, and the average flood duration will be 3.4 hr. Table 2 describes the implications of the three design levels in more detail. This table is based on the models developed.

Compared with criteria determined in other parts of the world, this approach represents an acceptable level of service. Coghlan (7)



(Note: Q_2 is the 1 in 2 year flood)

FIGURE 2 Time certain flows were exceeded for three drainage regions.



(Note: Q_2 is the 1 in 2 year flood)

FIGURE 3 Number of times certain flows were exceeded for three drainage regions.

quotes criteria for access consisting of maximum closure of 1 to 3 days at a time, totaling not more than 15 days a year. Shen (*8*) established through an opinion survey the following (modified) absolute constraints for LLRCs:

- Average annual frequency of possible flooding: 5 to 10 times; and
- Duration of average traffic interruption: less than 48 to 72 hr.

The following approach is suggested for determining the design level:

- Design Level 1 is taken as the initial choice;
- The design level is increased to Level 2: if the traffic volume exceeds 250 vehicles per day or if the additional length of alternative routes exceeds 20 km;
- The design level is increased to Level 3: if the traffic volume exceeds 500 vehicles per day or if the additional length of alternative routes exceeds 50 km; and
- Should there be no alternative route available, or if the road is of strategic importance, the designer must choose the design level based on the implications described in Table 2.

When the design level is known, the design flood is determined as follows:

$$Q_{\text{design}} = f_i \times Q_2 \quad (2)$$

where

Q_{design} = the design flood,
f_i = a dimensionless factor related to the design level chosen and shown in Table 2, and
Q_2 = the flood with a 1-in-2-year return period.

It was assumed that accommodating the total design flood under the structure would not be necessary; such an approach would have ruled out unvented structures (e.g., concrete slabs). Part of the design flood may be accommodated over the structure provided it is still safe for a vehicle to pass over the structure.

The structure should therefore be designed such that

$$Q_o + Q_u \geq Q_{\text{design}} \quad (3)$$

where Q_o is the flow that can be accommodated over the structure for flow depth less than the maximum acceptable and Q_u is the flow capacity under the structure.

FLOW DEPTH

It was accepted that a vehicle should not pass over an LLRC being overtopped if the depth of flow exceeds the underbody ground

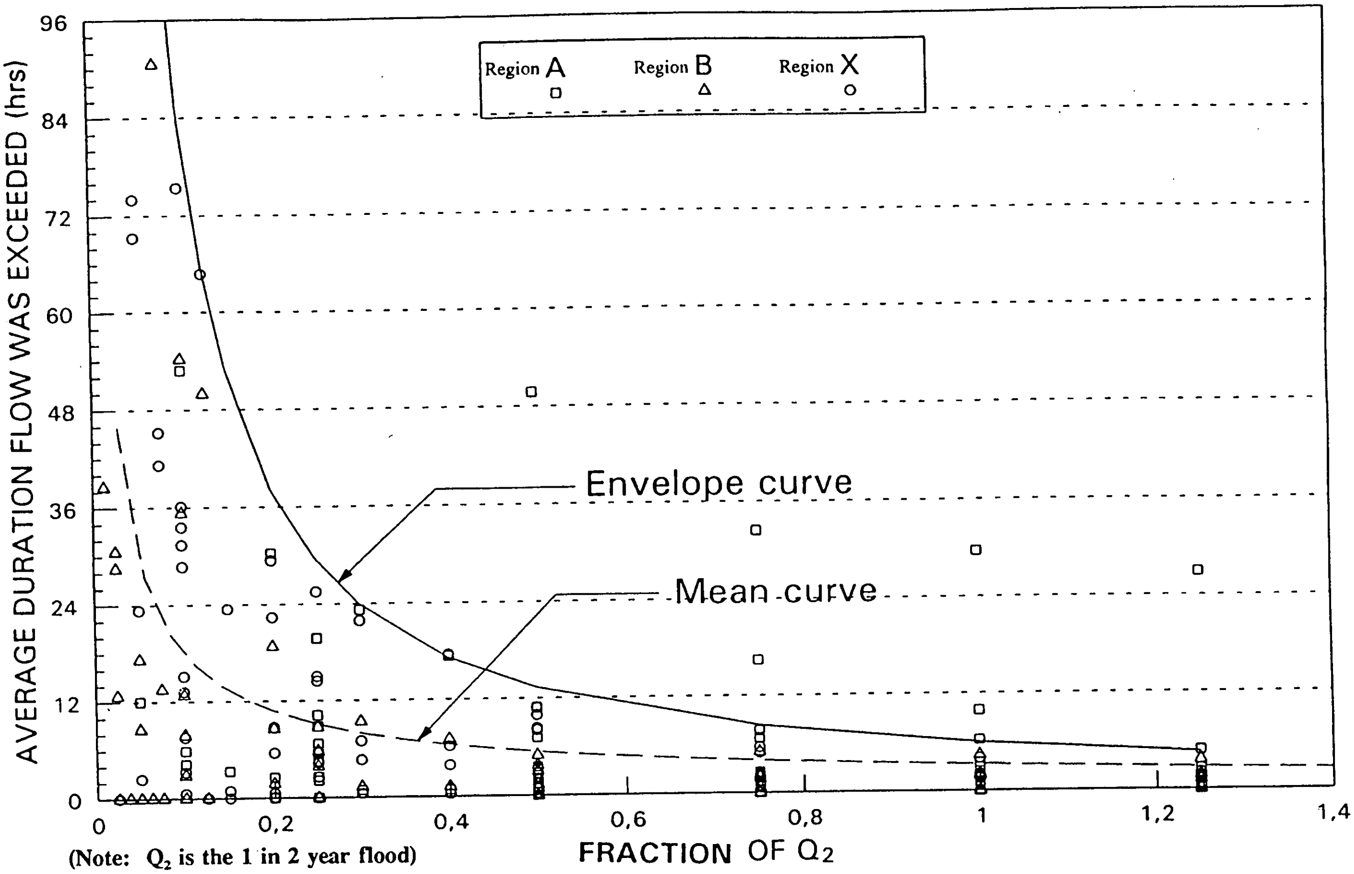


FIGURE 4 Average duration flow was exceeded for three drainage regions.

clearance height of the vehicle. The flow velocity, however, also must be considered.

The flow-depth relationship was determined for the following typical cross sections being used for low-level structures (Figure 5) (*9*):

- 5.5 and 8.5 m wide with a crossfall of 2 percent in the direction of flow,
- 8.5 m wide with a 2 percent camber, and
- 5.5 and 8.5 m wide with a zero-grade crossfall.

Based on the analysis, the following design values are recommended:

- Supercritical flow: maximum depth 100 mm, and
- Subcritical flow: maximum depth 150 mm.

The value of 100 mm was chosen for supercritical flow because at this depth, flow velocity was approaching 2 m/sec, which is relatively high. In the case of subcritical flow, 150 mm was chosen, as most passenger cars have this amount of clearance and flow velocities are generally less than 1 m/sec, which is not considered to present any danger to moving vehicles.

USE OF THE METHODOLOGY: SUMMARY

The use of the methodology is summarized as follows:

1. Determine the design level (f_i), taking into account traffic volume, importance of the route, and the availability of alterna-

TABLE 2 Levels of Design for Low-Level Structures

		AVERAGE NO OF TIMES EXCEEDED PER YR PER GAUGING STATION			AVERAGE DURATION PER FLOOD (HRS) PER GAUGING STATION		
DESIGN LEVEL	f_i	MINIMUM VALUE	MAXIMUM VALUE	AVERAGE VALUE	MINIMUM VALUE	MAXIMUM VALUE	AVERAGE VALUE
1	0.25	0	4.2	1.3	0	30	9.0
2	0.50	0	2.4	0.8	0	13	5.5
3	1.00	0	1.4	0.5	0	6	3.4

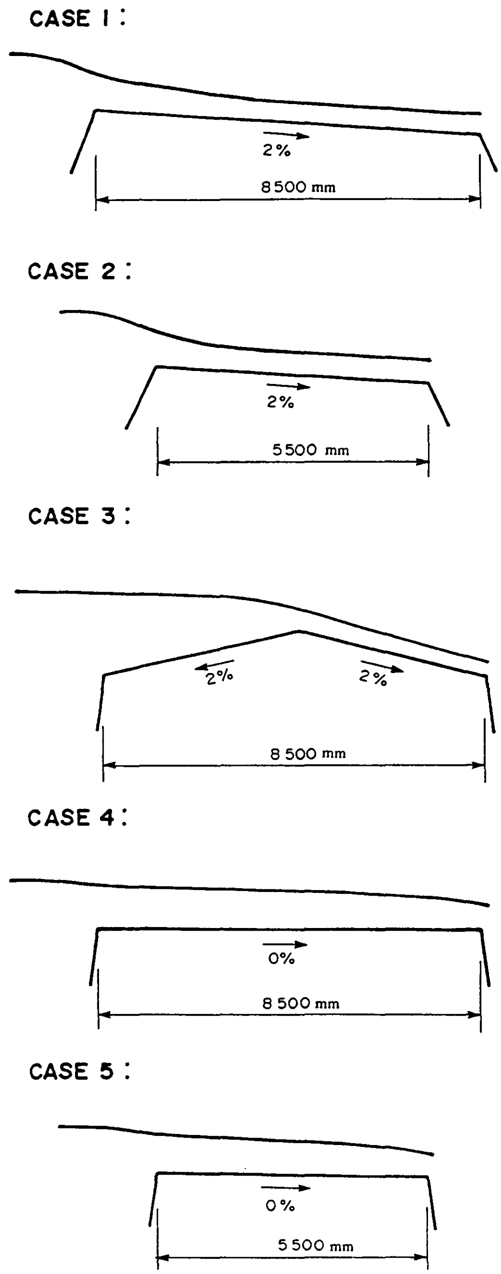


FIGURE 5 Typical cross sections used for low level river crossings.

tive routes. Table 2 quantifies the implications of the design level chosen.

2. Determine the 1-in-2-year flood (Q_2).
3. Determine the design flood: $Q_{\text{design}} = f_i \times Q_2$ (Equation 2).
4. Determine the road cross section and the (preliminary) road profile over the river.
5. Determine the flow that can be accommodated over the structure within the maximum acceptable flow depth (Q_o): 100 mm for supercritical and 150 mm for subcritical flow.
6. Determine the flow that must be accommodated underneath the structure: $Q_u \geq Q_{\text{design}} - Q_o$ (Equation 3).
7. Determine the dimensions of the opening(s) required underneath the structure if flow must be accommodated.
8. If it is necessary to adjust the road profile because of the dimensions of the opening(s), return to Step 4.

If the structure is outside the study area, the methodology should be applied with caution.

CONCLUSION AND RECOMMENDATION

Recent political changes in South Africa have led to an increased emphasis on rural areas and on the use of low-level river crossings. The study addressed the quantification of the implications of these structures being flooded. A design method for the selection of LLRCs was presented.

The methodology proposed can be beneficial to practitioners involved with the design of LLRCs. The authors recommend that the study area be extended to the whole of South Africa and later to other regions.

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