1998

Impact of fusegate rotation on a reservoir's firm yield

W.V. Pitman, Stewart Scott, South Africa
M.D. Watson, Department of Water Affairs and Forestry (DWA & F), South Africa
W.D. Hakin, Hydroplus International, South Africa.

A study has been carried out on behalf of the DWA & F involving 30 river catchment areas in South Africa to assess the possible impact on the firm yield of a reservoir caused by the rotation of a fusegate. The results can be applied to any catchment in the country.

The installation of fusegates on the spillway crest of an existing dam can be a cost-effective way of increasing the storage capacity of a reservoir and hence its firm yield*. However one area of concern regarding the installation of fusegates is that, after the first tipping, some or all of the increased storage could be lost. If such a loss were to occur just before the critical period** there may be insufficient time for the water to return to the new storage capacity level. In such cases the new firm yield would be reduced. To address this concern, a theoretical analysis was carried out on 30 catchment areas throughout South Africa, and in addition on two existing dams, one in Malawi and one in South Africa. The analysis, undertaken on historical streamflow and on stochastically generated time series, comprised the following steps:

- Establish the critical period determining the firm yield for three different dam sizes, that is, 50 per cent, 100 per cent and 200 per cent of mean annual runoff (MAR).
- Select a plausible reinstatement period immediately before the critical period for reinstallation of the tipped fusegate(s).
- Identify floods (if any) with a return period of 10 years or greater, that occurred during the reinstatement period.
- Summarise the results and establish trends.

The results showed clearly how the risk of rotation impacting on firm yield increases with the size of reservoir in relation to the MAR. The stochastic analysis also showed how increasing the return period of the flood, designed to initiate rotation, reduces the risk of impact on firm yield, regardless of the dam size. The study also demonstrated the degree to which the risk of impact on firm yield can be minimized by reducing the reinstatement period. No regional trends emerged from the study and there was also no correlation with the coefficient of variability of the historical streamflow.

It can therefore be concluded that the results can be applied to any catchment area in South Africa (and probably elsewhere). These results indicate that the risk of fusegate rotation impacting on firm yield is extremely low, especially if the first tip is designed to occur for floods of 100 year return period or greater, and that the reinstatement period is only of a few months' duration.

The rotation of fusegates

To maintain the capability of the spillway to pass extreme floods, it is essential that the fusegates rotate according to a predetermined tipping sequence to provide adequate passage for the floodwaters. The design return period for each sequence of rotation depends on several factors, such as the original spillway configuration, the increase in full supply level and the given flood hydrology. The first tipping sequence is usually designed to occur in the event of a flood with a 100 year return period, or greater.

A possible concern regarding the installation of fusegates to increase storage capacity is that, after the first tipping, some or all of the increased storage will be lost and that this loss could cause a reduction in the firm yield of a dam. As the firm yield is determined by the water balance of the dam over the critical period, any incidence of fusegate tipping that affects this bal-

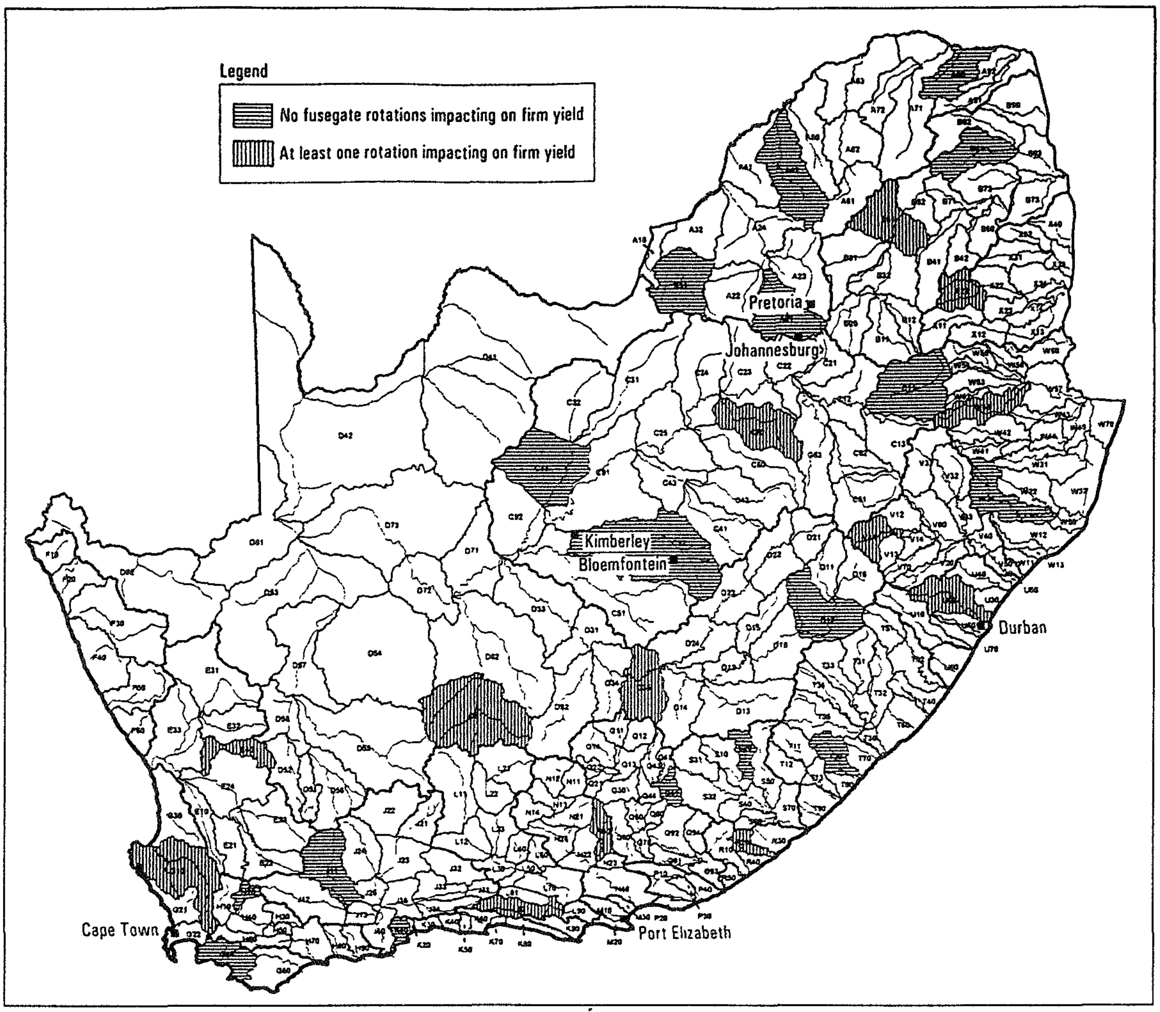
Table 1: Details of selected catchments

Catchment number	Catchment area (km²)	MAR (10^6m^3)	MAR (mm)	CV (std.dev./MAR)
A21	6336	209.5	33	0.785
A31	6684	94.5	14	1.156
A42	8395	312.3	37	0.882
A180	4203	113.2	27	1.190
B51	6170	46.6	7.5	0.821
B81	4952	381.0	77	0.797
C11	8791	548.1	62	0.689
C33	9843	37.1	3.8	2.364
C52	17366	185.6	11	1.374
C70	6656	192.3	29	0.851
D17	7179	1108.6	154	0.417
D35	5638	53.1	9.4	1.962
D61	13405	29.1	2.2	1.134
E40	2722	27.1	9.9	1.251
G10	8912	913.3	102	0.476
G40	3058	502.5	164	0.391
H20	832	99.2	119	0.760
J11	5646	37.9	6.7	1.500
K10	911	65.1	71	0.653
L82	2820	148.2	53	0.929
N30	1934	35.1	18	1.148
Q41	1292	24.7	19	1.228
R20	1286	108.5	84	0.908
S20	1607	65.7	41	0.739
T20	2600	392.2	151	0.512
U20	4439	739.9	167	0.560
V11	2635	915.9	348	0.393
W21	5274	464.4	88	0.843
W51	3894	570.5	147	0.538
X21	30912	507.9	164	0.416

*The firm yield is defined as the maximum supply that can be sustained throughout the historical period for which the hydrology is available.

**The critical period is defined as the period spanning the time from which a reservoir was last full to when it reached maximum drawdown. The length of the critical period can range between a few months and several years, depending on the capacity of the reservoir in relation to the average inflow.

Fig. 1. Tertiary catchments selected for historical analysis.



ance will also affect the firm yield. In the light of this concern, a study was undertaken to evaluate the probability of fusegate rotation causing a reduction in the firm yield of a dam.

Methodology of the study

The purpose of the study was not to investigate specific reservoirs, but to undertake a theoretical exercise covering the full range of hydrology likely to be encountered across South Africa. To this end, 30 catchments were selected as shown in Fig.1. Seventy year (1920 to 1989 hydrological years) time series of monthly natural flows for each catchment were obtained from the Water Resources of South Africa 1990 database (Midgley, Pitman and Middleton, 1994[1]). Relevant hydrological characteristics of each time series are given in Table 1.

For each time series, the seven largest monthly flows were identified and assigned return periods ranging from 70 years (largest) to 10 years (7th largest).

Table 2: Analysis of flood peaks and volumes*

Ranked maximum monthly flows		Peak discharge in month	
Volume (10^6m^3)	Return period (years)	Discharge (m^3/s)	Return period (years)
6493	36	7703	36
5825	18	6825	18
4710	12	3149	5.1
4037	9	3593	9
3557	7.2	5465	12

*Guage D3H003 on the Orange river

Although the largest event in 70 years would not necessarily have a return period of 70 years, the assumption is reasonable when one is analysing a large number of catchments. A further assumption is that a flood peak of return period *R* would occur in the month associated with a volume of return period *R*. Although this would not always be the case, it was considered to be a reasonable assumption for the purpose of this analysis. Furthermore, this assumption greatly simplified the stochastic analysis.

Long unbroken records that include all flood peaks can be analysed to verify this assumption. Unfortunately such records are sparse, since major floods often destroy the gauging equipment. As an example, Table 2 contains the results of an analysis of monthly flood peaks and volumes for a 35 year record on the Orange river. Closer examination of this Table shows that the two highest peaks occurred in the months with the highest volumes. For less severe events, the return periods of volume and peak do not always match but, since fusegates are usually designed to tip only during major floods, the assumption does indeed appear to be plausible.

The next step was to establish the firm yield sustainable over the full 70 years and to note the associated critical period. For this exercise, three theoretical dam sizes were analysed: 50 per cent MAR, 100 per cent MAR and 200 per cent MAR. The dam sizes are appropriate to the 'raised' situation, that is, with fusegates in place.

The critical periods span the time to maximum drawdown from when the dam was last full. It is extremely unlikely that the critical period would include a flood (that is a monthly volume) with a return period of 10 years or more. Even if this were to occur, the flood would be completely absorbed by the reservoir since, by definition, no spillage takes place during the critical period. However there is a distinct chance that a significant flood could occur a short time before the critical period begins. If this were to happen, it is possible that the fusegates (or stoplogs if provided) could not be reinstated and the loss in storage made good before the critical period began. To cater for such an eventuality, the critical period was extended backwards in time. If the fusegate rotated within the extended period before the critical period, it was assumed that insufficient time would be available for reinstallation or stoplogging, and storage recovery to the raised full supply level, hence the critical period would be extended with a consequent reduction in firm yield. (In this study no attempt has been made to quantify the reduction in firm yield.)

Two assumptions were made with regard to the extension of the critical period. A conservative period of five months was tested, in addition to a more realistic time scale of two months. The five-month period was selected to embrace the wet season preceding the onset of the critical period. With the use of stoplogs, however, it was assumed that storage could be reinstated within two months.

The position of each of the seven largest monthly flows was tested to ascertain whether overlap occurred with the extended critical periods. This check for overlap was carried out for the critical periods associated with each of the three dam sizes analysed.

Historical analysis

The procedure described was applied to each of the 30 time series, and note was taken of any occurrences of the seven largest monthly flows within the extended critical periods. Results of the historical analysis are summarised in Table 3 and shown in graphical form as Figs. 2a and 2b. Probabilities are expressed as annual probabilities, which indicate the risk of rotation impacting on firm yield in any given year. The reinstatement delay indicated in the diagrams is equal to the critical period extension.

Table 3: Historical analysis summary

Flood return period (years)	Rotations for dam sizes of (per cent MAR)			Total no of rotations
	50	100	200	
70	–	–	–	0
35	L82 (5)*	L82 (5) V11 (2)	L82 (4) U20 (3)	5
23.3	–	D35 (3) E40 (3)	D35 (3) E40 (3) W51 (2)	5
17.5	–	–	–	0
14	–	B51 (4) R20 (2)	B51 (2)	3
11.7	C70 (4)	G10 (5)	G10 (5) N30 (2)	4
10	–	–	D61 (2) X21 (4)	2
Total failures (five month extn.)	2	7	10	19
Total failures (two month extn.)	0	2	4	6

The code before the bracket refers to the catchment analysed (see Table 1) and the figure in brackets is the time elapsed (in months) between rotation and startof critical period.

Fig. 2a shows a definite trend of increasing probability of fusegate rotation having an impact on firm yield with increasing dam size. This trend can be attributed to the behaviour of dams of varying size (relative to the MAR) when operated on a firm yield basis. Small dams remain relatively full for most of the time, and a significant flood is not required to fill them. On the other hand, large dams fill on relatively few occasions, and it usually requires a large flood to fill them. Since a critical period begins when the dam is full, it is therefore more likely for a flood to occur just before the critical period in the case of a large dam.

The relationship between flood return period and the probability of the flood impacting on firm yield (that is to say, occurring within the extended critical period) appears to be fairly random (see Fig.2b). However there were no cases of 70 year floods overlapping with critical periods in any of the catchment areas analysed. The absence of a clear relationship between increasing

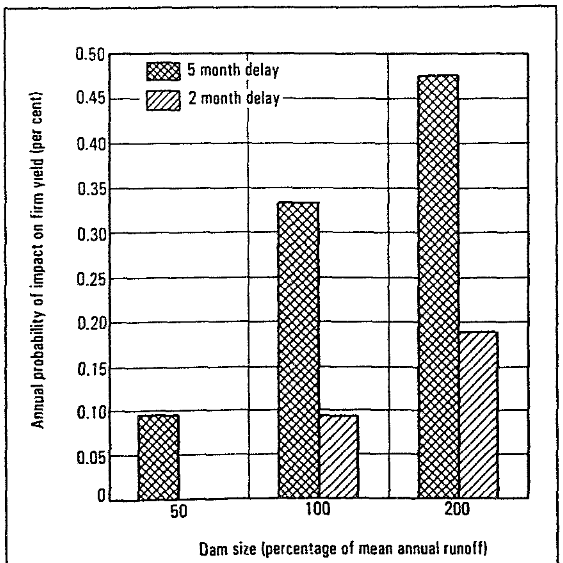


Fig. 2a. Historical analysis: effect of ***dam size*** *and reinstatement delay on the probability of rotation impacting in the firm yield.*

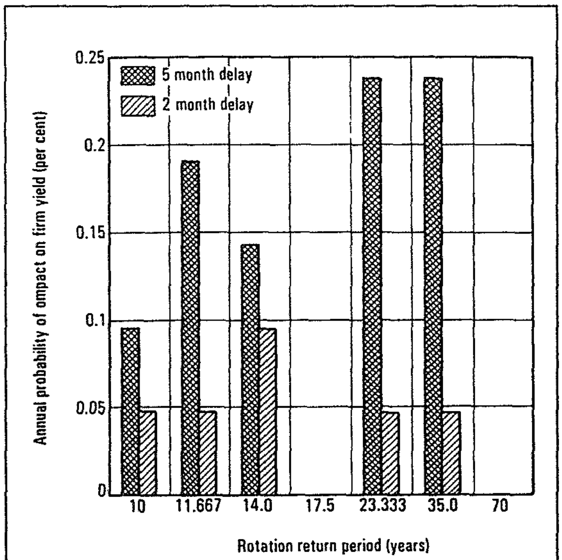


Fig. 2b. Historical analysis: effect of ***rotation return period*** *and reinstatement delay on the probability of rotation impacting on the firm yield.*

Table 4: Flood classification

Class	Range in return period	Expected number of (in 2870 years)
1	10-15	96
2	15-20	48
3	20-30	48
4	30-50	39
5	50-100	28
6	100-200	14
7	>200	14

flood return period and a decreasing probability of flood impact on firm yield may be attributed to the relatively small sample size of 30 historical sequences.

In 13 of the 30 catchments analysed at least one case of rotation occurred in the extended five month critical period. The distribution of these catchments (see Fig.1) appears to be completely random, which suggests that none of the regions can be seen as having an elevated risk of fusegate rotation close to the start of a critical period.

A shortening of the critical period extension (reinstatement delay) from five to two months reduces the total number of rotations by about two-thirds. The implication of this result is that the probability of rotation impacting on the yield can be reduced significantly by prompt action such as stoplogging.

Stochastic analysis

Since fusegates are usually designed to rotate for floods with return periods greater than 70 years, it was necessary to undertake a stochastic analysis to ascertain the risk of such floods impacting on the firm yield.

For the stochastic analysis, 41 seventy-year sequences were generated for each of the 30 catchments. The GENMAC suite of computer programmes was used for this purpose (McKenzie and van Rooyen, 1997[2]). The 41 sequences were then analysed in a similar fashion to the historical time series with the exception of the following step.

The seven largest floods in each sequence were assembled together to form a list of 287 (that is, 7 × 41) values. These were ranked in descending order and assigned appropriate return periods. For example, the return period of rank 1 is 2870 years (the total number of years generated) and that of rank 287 is 10 years (2870/287). The floods were then classified according to seven ranges, shown in Table 4.

Flood events falling within the five-month and two-month periods before the critical period were noted according to dam size and return period classification. Results of the stochastic analysis are summarized in Tables 5 and 6.

The data in Tables 5 and 6 indicate a clear trend of increasing likelihood of fusegate rotation with

Table 5: Stochastic analysis summary (five month extension of critical period)

Return period period (years)	*Rotations for dam sizes of (per cent MAR)			Total no of rotations
	50	100	200	
10-15	39	47	73	159
15-20	19	32	47	98
20-30	17	19	34	70
30-50	6	12	30	48
50-100	4	10	21	35
100-200	1	5	18	24
>200	1	2	8	11
Total	87	127	231	445

*Of a total of 1230 (30×41) generated sequences

Table 6: Stochastic analysis summary (two month extension of critical period)

Return period period (years)	*Rotations for dam sizes of (per cent MAR)			Total no of rotations
	50	100	200	
10-15	16	15	29	60
15-20	7	12	25	44
20-30	9	11	14	34
30-50	2	4	9	15
50-100	2	5	8	15
100-200	0	2	8	10
>200	0	0	4	4
Total	36	49	97	182

*Of a total of 1230 (30×41) generated sequences

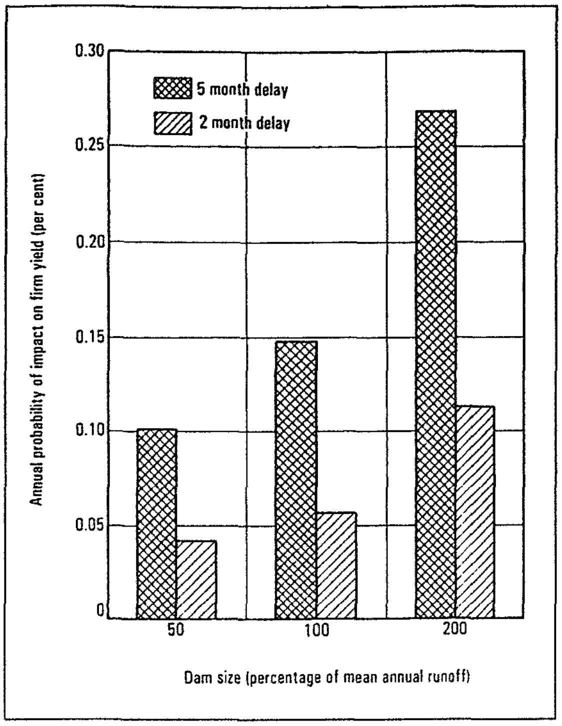


Fig. 3a. Stochastic analysis: effect of ***dam size*** *and reinstatement delay on the probability of rotation impacting on the firm yield.*

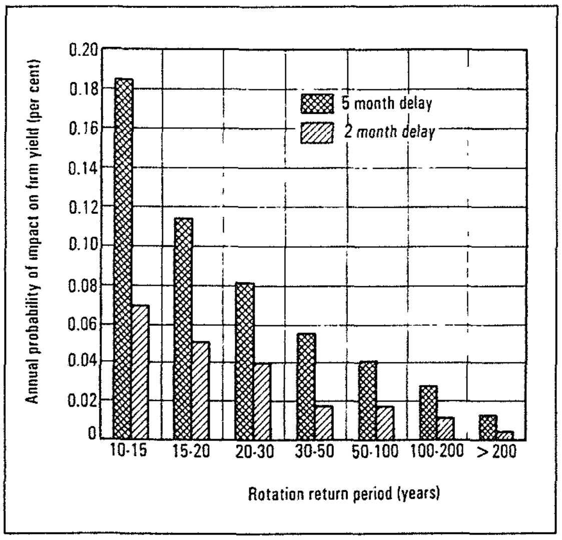


Fig. 3b. Stochastic analysis: effect of ***rotation return period*** *and reinstatement on the probability of rotation impacting on the firm yield.*

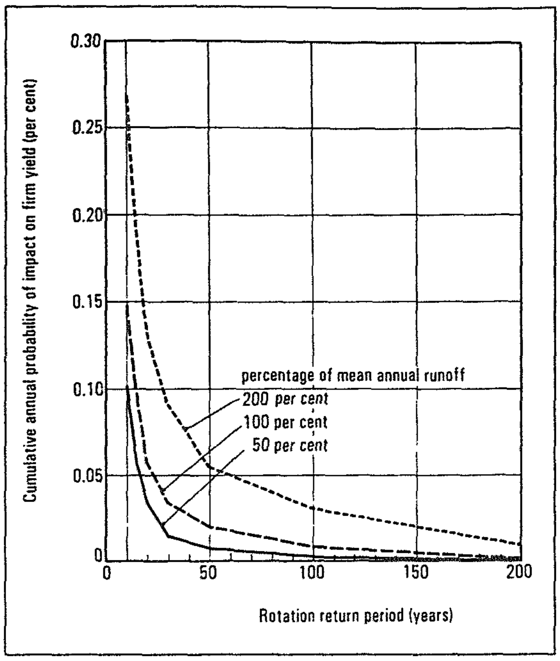


*Fig. 4a. tochastic analysis: effect of dam size (per cent MAR) and rotation return period for a **five** month reinstatement delay.*

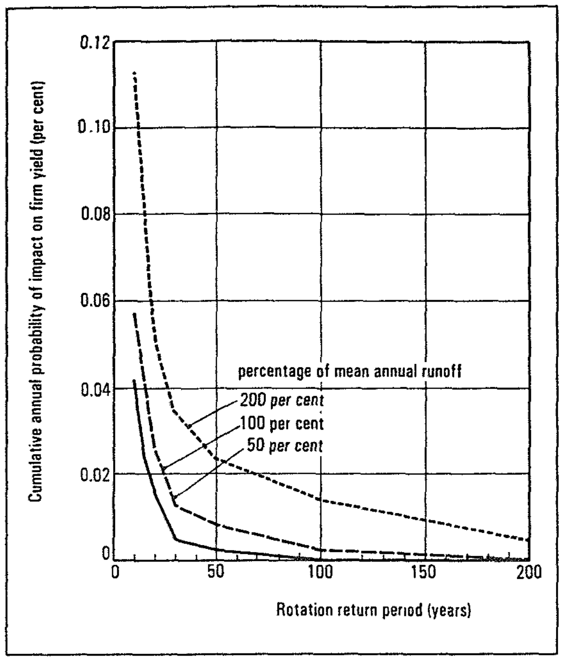


*Fig. 4b. Stochastic analysis: effect of dam size (per cent MAR) and rotation return period for a **two** month reinstatement delay.*

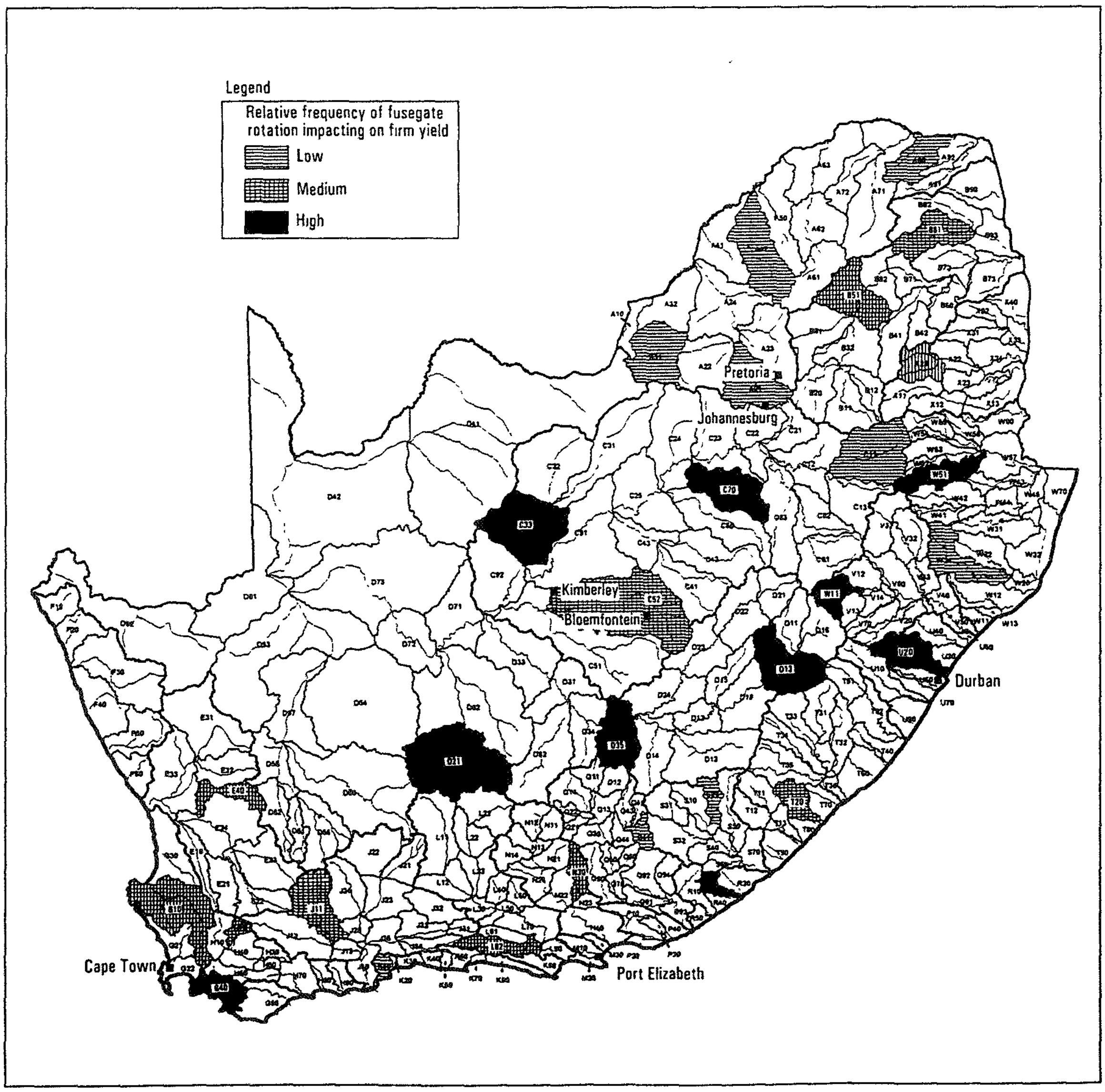


Fig. 5. Tertiary catchments: stochastic analysis.

increasing dam size (in relation to the MAR), supporting the results of the historical analysis. The Tables also reflect a decreasing likelihood of rotation with increasing return period. Such a result is not unexpected, but the historical sample size was too small to give any indication of such a trend.

The results in Tables 5 and 6 are shown in graphical form in Fig. 3a (effect of dam size) and Fig. 3b (effect of rotation return period), with occurrences expressed as probabilities. A comparison of Figs. 2a and 3a shows the probabilities derived from the stochastic analysis to be generally lower than those derived from historical data. Figs. 3a and 3b show the probabilities for the two-month reinstatement delay to be of the order of 40 per cent of those derived for the five-month period. It should be emphasized again that the probabilities given are annual probabilities, which indicate the risk of rotation impacting on firm yield in any given year.

Figs. 4a and 4b show the cumulative probability of rotation of a fusegate designed for a flood of given return period for dam sizes of 50 per cent, 100 per cent and 200 per cent MAR. (The cumulative probability is defined here as the cumulative probability of all events equalling or exceeding the return period in question). The diagrams show clearly how the risk of rotation just before a critical period increases with increasing dam size to MAR ratio, and decreasing return period. For example, Fig. 4a shows that a fusegate designed to tip in a 50-year flood would have an annual risk of rotation (within five months of a critical period) of slightly more than 0.05 per cent if the dam size were 200 per cent MAR. However for a dam size of 50 per cent MAR, the annual risk is less than 0.01 per cent. If the return period of rotation of the 50 per cent MAR were to be reduced to 15 years the annual risk would increase to about 0.05 per cent.

Fig. 4b indicates clearly the reduced risks associated with fusegate rotation within two months of the critical period. A fusegate designed to tip in a 50 year flood would have an annual risk of rotation of about 0.025 per cent if the dam size were 200 per cent MAR. For a dam size of 50 per cent MAR, the risk is less than 0.005 per cent. If the return period of rotation with the 50 per cent MAR dam were to be reduced to 15 years, the increased risk would still be less than 0.025 per cent on an annual basis.

The results presented in Table 4 and Figs. 3 and 4 are based on the stochastic analysis of the full sample of 30 catchments. To give a qualitative assessment of vulnerability to fusegate rotation impacting negatively on the firm yield, the catchments have been classified into three groups of ten, indicating low, medium and high (relative) probability of rotation. This simple classification is shown in Fig. 5. As was the case for the historical analyses, no regional pattern emerged. There is also no correlation with the variability (CV) of the historical time series. For example, the 'high' category embraces catchments of very low CV (for example, G40 and U20) and very high CV (for example, C33 and D61).

Case studies

Kamuzu II dam, Malawi

It is proposed to increase the height of this dam by 5 m with the installation of fusegates. This will increase the capacity from 8.9 to 19.8 × $10^6 m^3$. The first fusegate is designed to tip at a discharge of 784 m^3/s, which is approximately equal to the 200-year flood. A stochastic analysis yielded a minimum gap of 90 months between a flood of 200 year return period or greater, and the start of the critical period, thus implying a negligible risk of rotation within the permitted two month reinstatement period. Such a result was to be expected, as the increased capacity is only 14 per cent MAR.

Midmar dam, South Africa

There were originally two proposals for heightening this dam with fusegates. The existing capacity of 159.2 × $10^6 m^3$ can be increased with fusegates to 247.2 × $10^6 m^3$ by raising the height of the dam by 4 m or to 257.2 × $10^6 m^3$ by raising the height by 4.57 m. When increased, the capacity will be approximately 125 per cent MAR. For both options, the first rotation is designed to occur for an inflow of 1800 m^3/s, which is slightly larger than the 200-year peak. A stochastic analysis generated one case out of a total of 41 of a 36-year flood occurring within the two-month reinstatement period, but not a single case of a 200-year (or greater) flood occurring before a critical period. These results suggest a negligible risk of fusegate rotation impacting on firm yield, which is in accordance with the theoretical study.

Summary and conclusions

Generally the study indicates the extremely low risk of floods of sufficiently large magnitude to cause a fusegate to rotate actually occurring just before the critical period.

The results show the risk of reduction in firm yield increasing with the size of reservoir. As a rough approximation, doubling the reservoir size to MAR ratio will also double the risk. The stochastic analysis also showed how the probability of impacting on firm yield can be reduced by increasing the return period of rotation of the first fusegate, regardless of the dam size. The probability of impacting on yield can also be minimized by reducing the period required to reinstate storage after rotation has occurred.

The results of the study are summarized in Figs. 4a and 4b, which present the interrelationship between reservoir size, rotation return period and probability of rotation impacting on firm yield. Figs. 4a and 4b can be considered to apply to any catchment in South Africa, since no regional or other trends emerged from the study. Fig. 4a can be used to aid decision making by showing, for example, that there is an annual risk of about 0.01 per cent (equivalent to a less than 1 per cent chance in a period of 70 years) that the increased yield of the dam (with increased storage equivalent to one MAR or less) would be reduced by a tip with the first fusegate designed to rotate for floods in excess of the 100-year event. This is based on the conservative assumption that the increased storage capacity cannot be regained in the five months following the tip.

Fig. 4b clearly shows how the probability of fusegate rotation impacting on yield can be reduced if this five-month period can be shortened to two months. The 0.01 per cent annual risk associated with the five-month period (see previous paragraph) can be reduced to less than 0.005 per cent.

The main shortcoming of the study lies in the use of monthly data throughout. Floods are short-duration events and, for example, the 100-year flood would not necessarily coincide with the monthly inflow of similar return period, as has been assumed in the analysis. It should also be appreciated that no attempt has been made to assess the degree of impact on firm yield. In practice it may be possible to restore some of the additional storage originally created by the installation of fusegates. The degree of impact will be governed by how much of the additional storage can be restored before the onset of the critical period.

It is suggested that the techniques used in this study could be applied to other dams where the use of fusegates to increase storage capacity is under consideration. ◊

References

1. **Midgley, D.C., Pitman, W.V., and Middleton, B.J.**. "Surface Water Resources of South Africa", Water Research Commission Report Nos. 298/1/94 to 298/6.2/94 (13 volumes): 1994.
2. **McKenzie, R.S., and Van Rooyen, P.G.**, "GENMAC Users Guide". BKS. Pretoria. South Africa: 1997.

Malcolm Watson is currently chief engineer for the Water Resources Planning Department for the Central region of South Africa (Orange and Vaal river basins). After graduating from the University of the Witwatersrand with a BSc(Eng) in 1979 and a Msc in 1981, he worked for a consulting company specialising in water engineering until 1994 when he joined the Department of Water Affairs and Forestry.

Dr W.V. Pitman is acknowledged as being one of the leading hydrologists in southern Africa. In addition to being the founder of the widely used Pitman catchment hydrological model and its successor, the WRSM90 model, he has played a prominent role in the development of southern African water resources and flood design manuals. He and his team have undertaken numerous hydrological and water resource studies. Dr. Pitman has been honoured by his peers with several prestigious awards for his contributions in the field of hydrology.

Bill Hakin is the Chief Executive of the South African branch of Hydroplus International. Since graduating from the University of Bradford in 1982 with a BSc (Eng), he has worked for various contracting and construction engineering firms.

Hydroplus International. PO Box 8015. Roggebaai 8012. Cape Town. South Africa.

W.V. Pitman

M.D. Watson

W.D. Hakin

FIRST EU-CHINA SMALL HYDRO INDUSTRY CONFERENCE

Accelerating Technical Cooperation and Market Development in Small Hydro
19 to 21 April 1999
Hangzhou, China

Hosted by the International Network for Small Hydropower, Hangzhou, China, in collaboration with THERMIE, DFID and IT Power Ltd.

OBJECTIVES
- To facilitate commercial co-operation between the SHP industries of China and the European Union;
- To bring together those with an interest in developing SHP projects, those with the technology to implement such projects, and those seeking capital investment opportunities;
- To clarify the barriers to the more rapid global development of SHP, and exchange ideas on how address these barriers;
- To present detailed information on the strengths and weaknesses of the EU and Chinese Small Hydro Industries;
- To propose a strategy for the accelerated implementation of SHP projects in the new millenium.

The conference is designed for those interested in developing business opportunities and collaborations in Europe, China and SE Asia in the field of small hydropower (<10MW), whether as project financiers, developers, equipment suppliers, designers, or consultants.

FOR FURTHER INFORMATION CONTACT:
Oliver Paish, IT Power Ltd
The Warren, Bramshill Rd,
Eversley, Hampshire, RG27 0PR
Tel: +44 118 973 0073
Fax: +44 118 973 0820
E-mail: ofp@itpower.co.uk

CIGB ICOLD CBGB

XXIII Brazilian National Symposium on Large Dams

The next National Symposium on Large Dams to be organized by the Brazilian Committee of ICOLD with the support of CEMIG, will take place from 22 to 26 March 1999 at the Ouro Minas Palace Hotel, Belo Horizonte. The working language of the meeting will be Portuguese.

The principal themes will be:

1. Institutional aspects - Privatization
2. Dam safety - Instrumentation - Refurbishment
3. Environmental aspects
4. Design and Construction

For further information, contact:

Comitê Brasileiro de Grandes Barragens
Rua Real Grandeza, 219 - Bloco C - Sala 903.2
CEP 22281-03 Botafogo, Rio de Janeiro, RJ, Brazil
Fax: +55 21 528 5959

Or visit the web sites:

www.cemig.com.br
(select option CEMIG Seminários)
and
www.cbgb.org.br

The Symposium is being organized with the support of:

CEMIG Companhia Energética de Minas Gerais