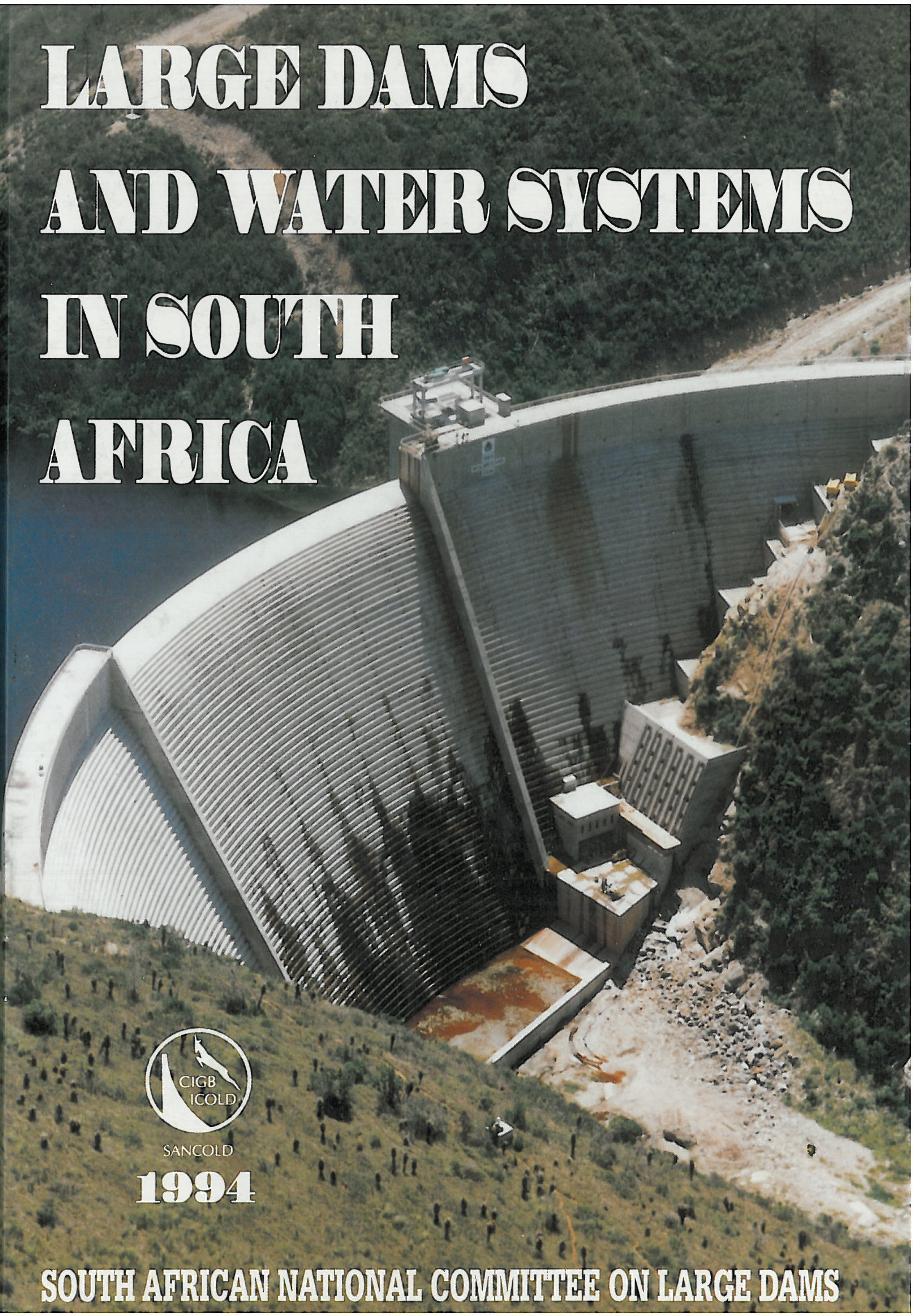
LARGE DAMS AND WATER SYSTEMS IN SOUTH AFRICA



CIGB
ICOLD
SANCOLD

1994

SOUTH AFRICAN NATIONAL COMMITTEE ON LARGE DAMS

LARGE DAMS AND WATER SYSTEMS IN SOUTH AFRICA

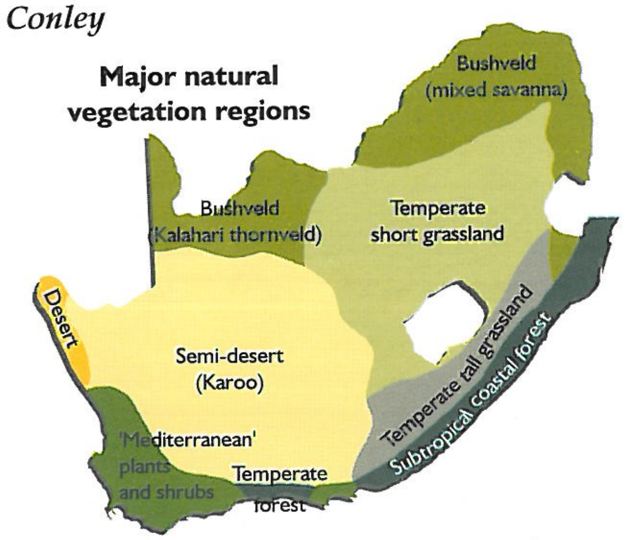
THE WATER RESOURCES OF SOUTH AFRICA

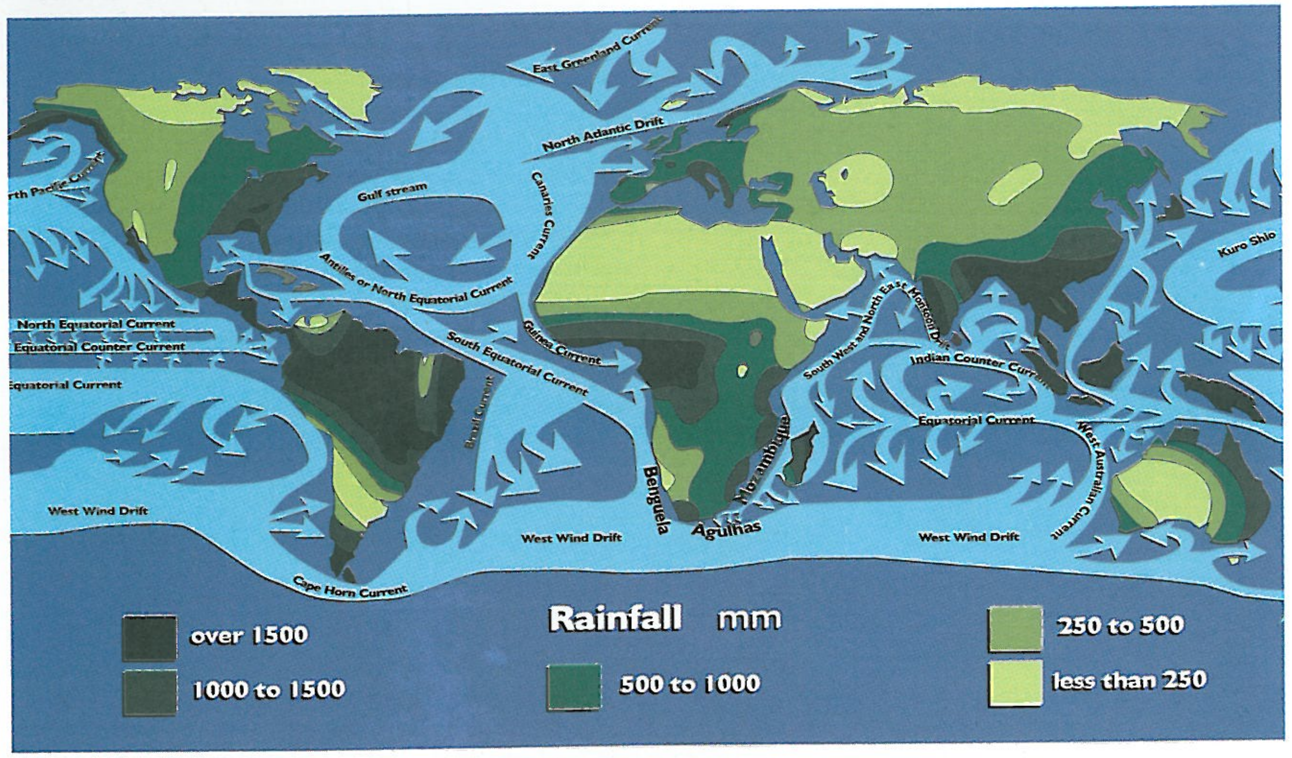
by A H Conley

THE COUNTRY

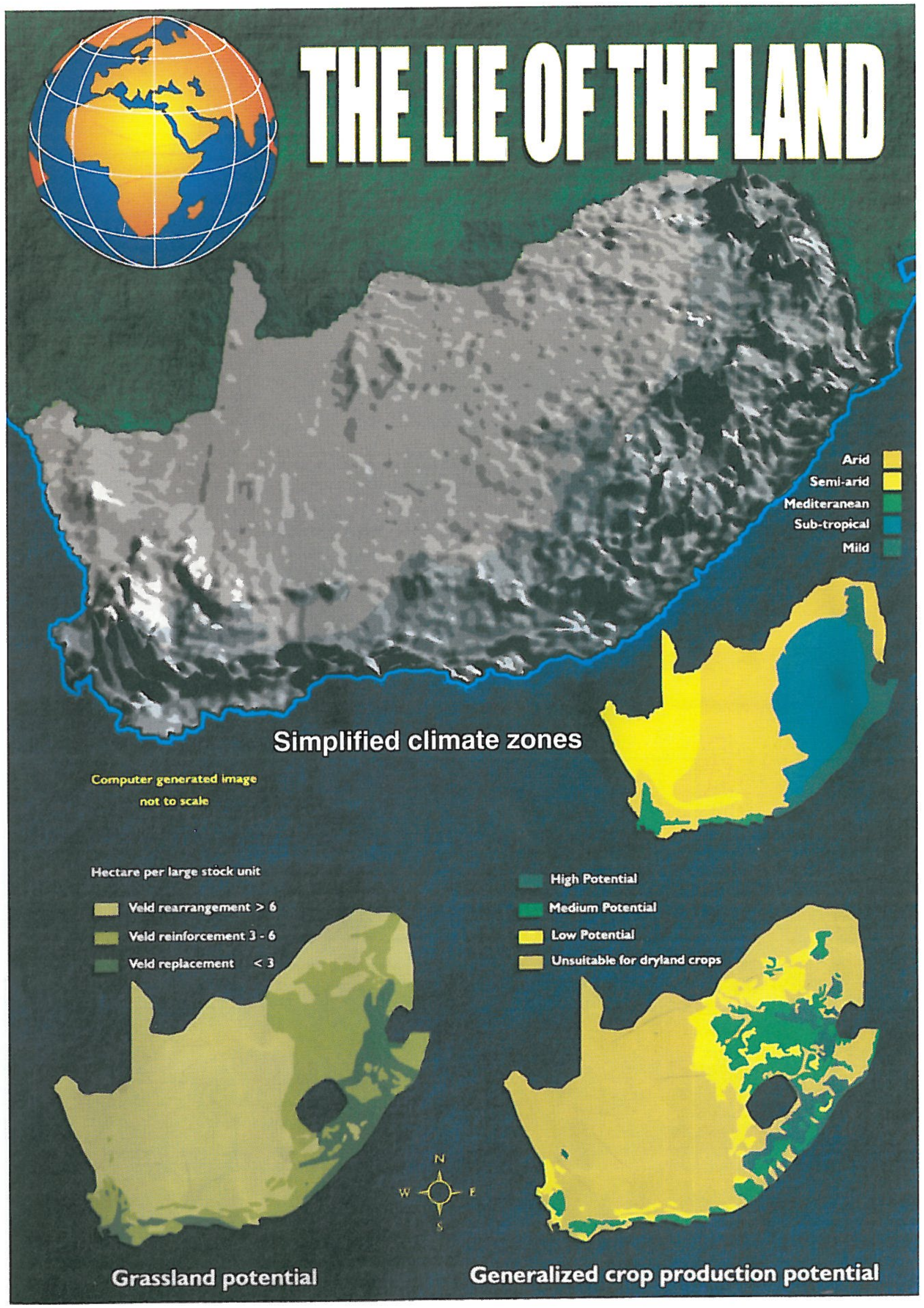
South Africa is a shield-shaped territory, 1 223 410 km² in extent, located between the Atlantic Ocean and the Indian Ocean at the tip of the African continent. It extends from Cape Agulhas in the south to the Limpopo River in the north. It is situated in a subtropical region of the world where the rainfall is unreliable, unevenly distributed, and prone to erratic, unpredictable extremes in the form of droughts and floods. On average, only 9% of the rainfall reaches the river systems. The topography, soils and climate are very diverse, requiring good management to gain the most benefit from the resources. Being mostly semi-arid, large parts of the country can not sustain a substantial growth of population or support modern standards of living without benefication of the natural environment.

The surface of South Africa is underlain mainly by old, stable parts of the earth's crust which contain relatively little groundwater. The interior of the country consists of a warped plateau which slopes gradually downwards from a height of 3 500 m in the eastern peripheral highlands to 900 m in the interior Kalahari Basin in the north western Cape. This is the end of the Great African plateau that extends northwards to the Sahara. The southern end of the plateau consists of uplifted, ancient hard rock formations overlain by eroded sedimentary deposits. The northern region within South Africa tilts downwards to the east. The prominent rim of the plateau, or Great Escarpment, consists of a number of mountain ranges which separate it from the marginal lands along the coast. They slope down to the sea, having been formed by the erosion of the edge of the escarpment. Their character varies according to the type of rock from which they originated. The marginal area has a western and an eastern zone, separated by the Cape Folded Region. Its width varies from 60 km in the arid west, to 240 km in the better watered south-east.





South African climate producing factors related to world-wide climate driving systems



CLIMATE AND RAINFALL

South Africa lies within the semi-permanent subtropical high-pressure belt of the middle latitudes of the Southern Hemisphere. Latitude, altitude, topography and oceanic influences give rise to a wide range of climatic conditions.

A global belt of warm, dry air, which descends from higher altitudes, is situated along latitude 30° south (through Durban and Port Nolloth). This high-pressure zone is maintained by air which rises by convection from the equatorial regions before it spreads poleward and sinks over the subtropics. Although the rising arm of this circulation is favourable for rain, the descending regions form warm temperature-inversions near the earth's surface, which inhibit cloud formation and rain.

During the southern winter this entire circulation moves northward, straddling South Africa with high-pressure, rainless conditions. During the southern summer the high-pressure belt moves south and weakens, allowing air which carries more moisture to promote rainfall in the summer rainfall areas.

Another global air circulation system is situated to the south of the country. This is the westerly wind belt which, driven by the rotation of the earth and local heating by the sun, creates a series of lowpressure systems. These individual circulations form a succession of cold and warm fronts which provide rain as they sweep eastward around the globe.

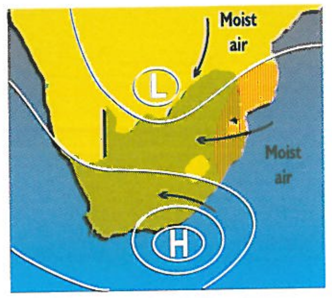
Over the Atlantic and Indian Oceans, the semi-permanent high-pressure systems also help to maintain the ocean currents, which are an important factor in the formation of rain.

In the Indian Ocean the southward-flowing Agulhas current is warm, so it contributes moist air to the eastern regions of the country. In contrast, the northward flowing Benguela current in the Atlantic Ocean is cold, giving rise to an inversion layer of warm air over cold air. This system restricts rainfall, so the western parts of the country tend to be dry and have deserts close to the ocean.

The changing position of the sub-tropical high-pressure belt dominates the rainfall distribution over South Africa. When it is situated above the interior, as in winter, dry, rainless conditions prevail. When the Atlantic cell of high pressure is dominant, cool southerly winds predominate, which give little rain, except over the south-western Cape region where the rain falls in winter. However, when the Indian Ocean cell of high-pressure is dominant, the warm, moist north-easterly winds favour rain, although the temperature-inversion tends to limit the rainfall to low altitudes (below the plateau) during winter. When the pressure is low over the interior of South Africa, the circulation favours rain, especially in the summer when moist air enters the low-pressure zone from the tropics. Occasionally, when the high-pressure cell extends southward of the south coast and the pressure is also low over the interior of the country, the circulation is conducive for heavy and extensive rain, which may cause floods.

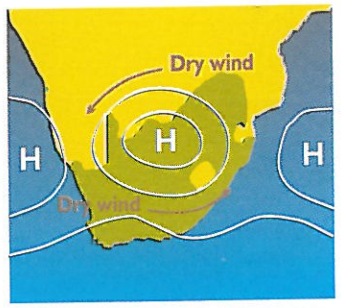
Global circulation belts producing Southern African weather systems

Anticyclone to south



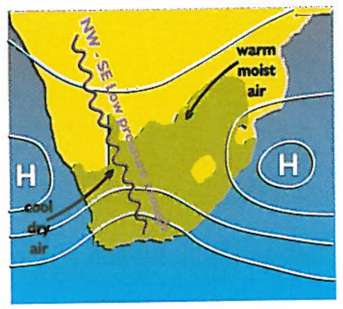
General eastern summer rain

Dry subsiding winds over plateau

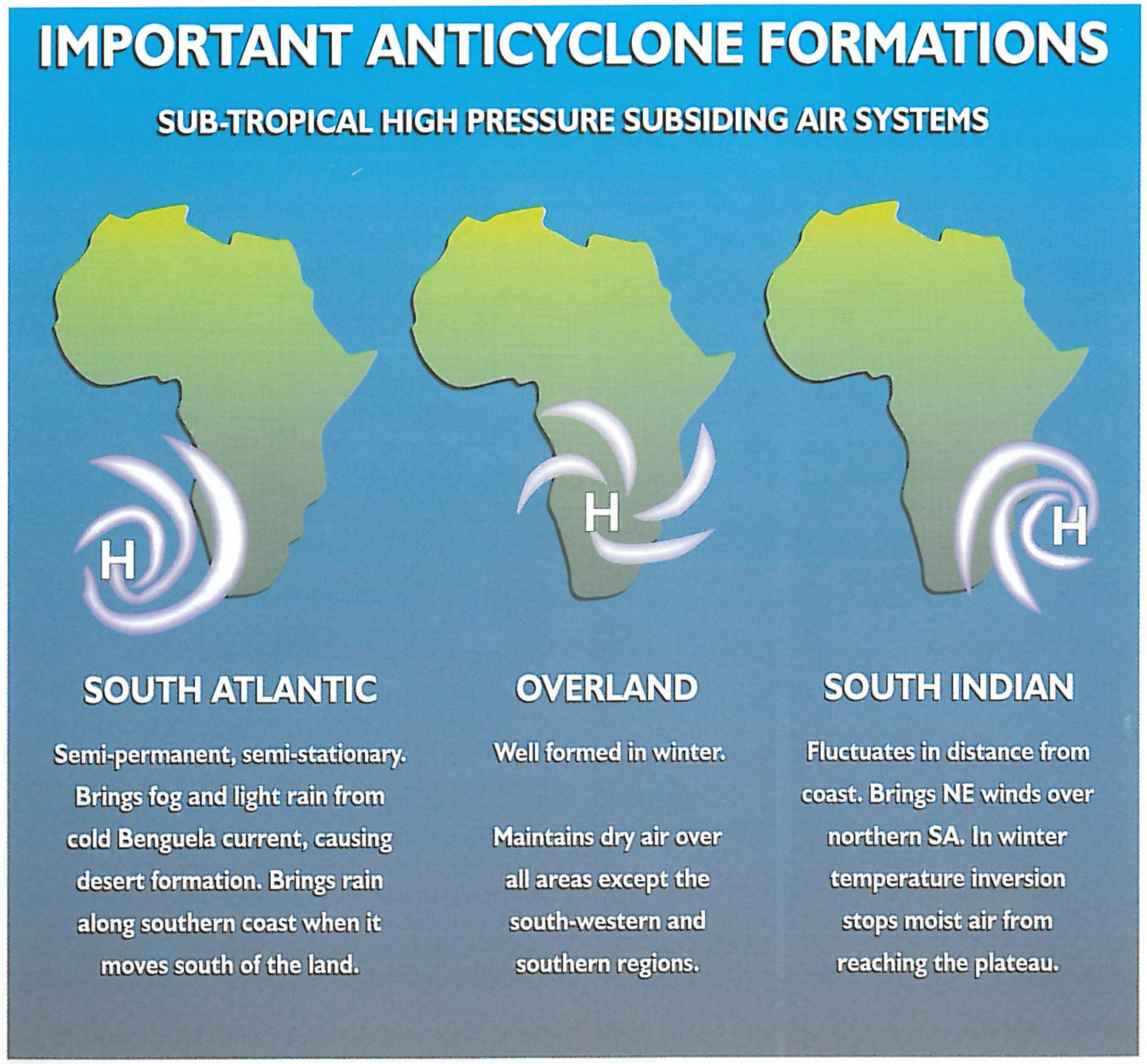


Winter anticyclone over land

Dry air from south-west and moist air from north-east Indian ocean cell dominates

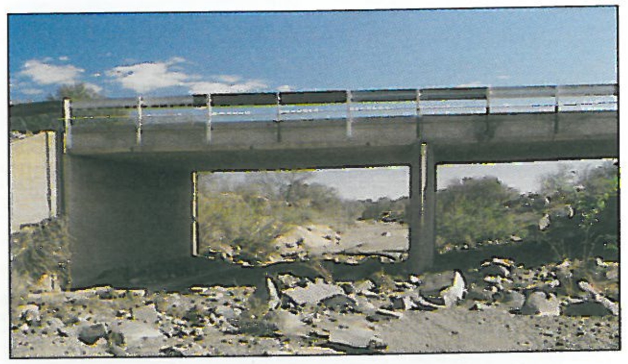


Summer thunderstorm conditions



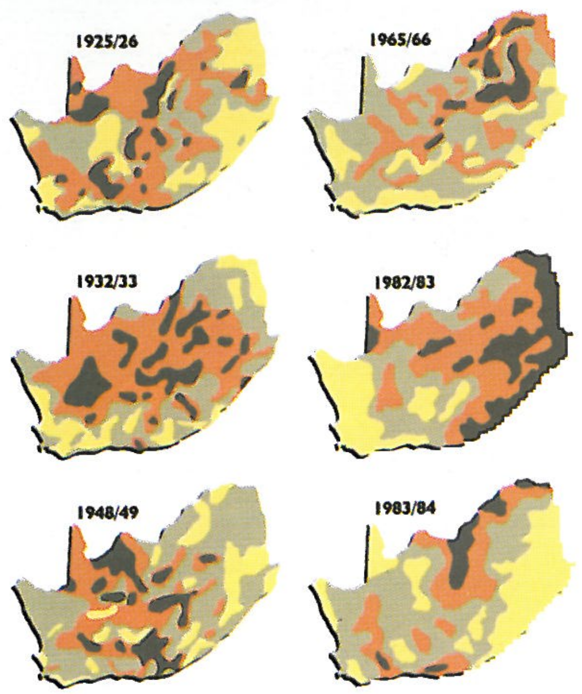
Droughts and floods

As a consequence of its situation and topography, South Africa is characterised by hydrological extremes. The country is periodically afflicted by

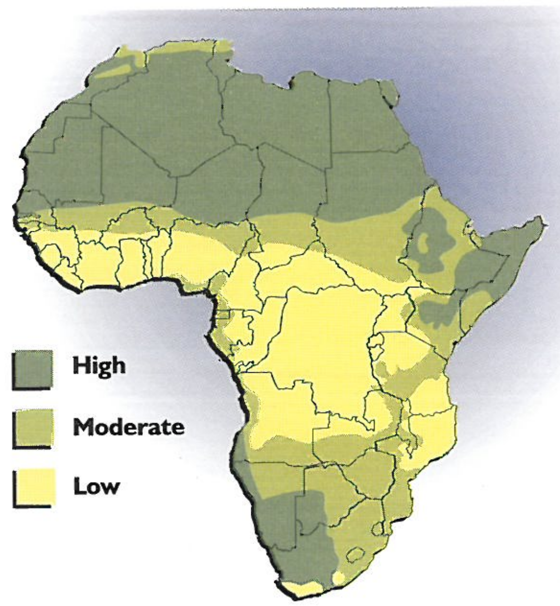


Drought: Typical South African dry river bed

Flood: Douglas flooded in 1988



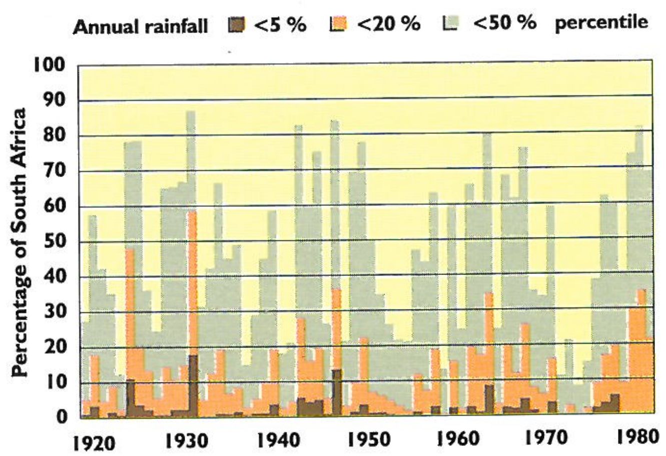
Typical severity of drought occurrences



Drought risk in Africa

severe and prolonged droughts, which may be terminated by severe floods. As illustrated, droughts of differing severity can occur anywhere at any time.

Droughts and floods may occur simultaneously in different regions of the country, even in adjoining watersheds. Heavy floods in the summer rainfall region of the interior of the country normally arise from the trapping of a low-pressure system over the interior by high-pressure systems in the Indian and Atlantic Oceans. Under these conditions warm, moist air drawn from the north and north-east may cause moderately heavy rain for several days, producing widespread floods. On the other hand, smaller convectional systems such as cloud mergers can produce short torrential rainstorms over a few square kilometres only. Tropical cyclones, which can cause heavy widespread rain, occasionally penetrate as far south as



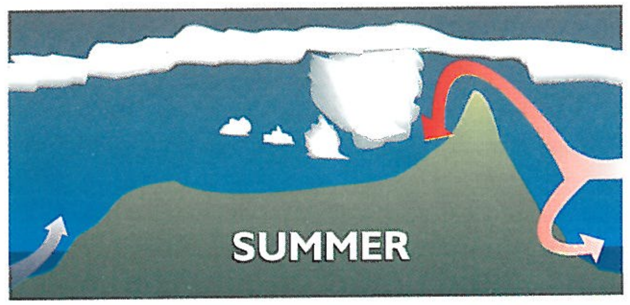
Local drought history of South Africa

the eastern Transvaal lowveld, Swaziland, Mozambique and northern Kwa-Zulu-Natal. The major flood-producing rainfall mechanisms in the southern Cape and the Karoo are cut-off low-pressure systems.

Rainfall regions

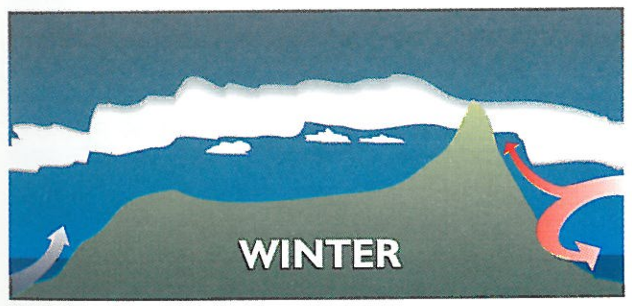
South Africa has three main rainfall regions, namely a relatively narrow winter rainfall region along the western and south-western coasts, a transitional all-year-round rainfall region along the south coast and a summer rainfall region in the rest of the country.

The seasonal distribution of rainfall is caused by



Summer weather pattern

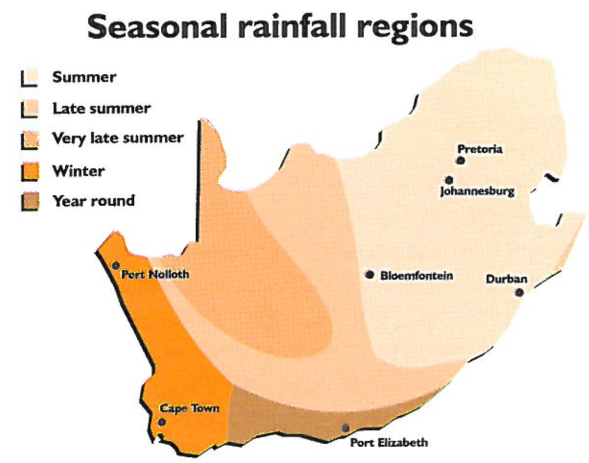
changes in the high-pressure systems and the height of the inversion layer. The heat of summer lifts the inversion layer above the level of the escarpment, allowing low-pressure troughs to develop periodically over the interior of the country. These troughs are oriented roughly north-west and south-east. They draw in moist air from the north and north-east, which rises, cools and produces rain. These convergent systems are the source of most of the rain in the interior of South Africa, although their influence diminishes

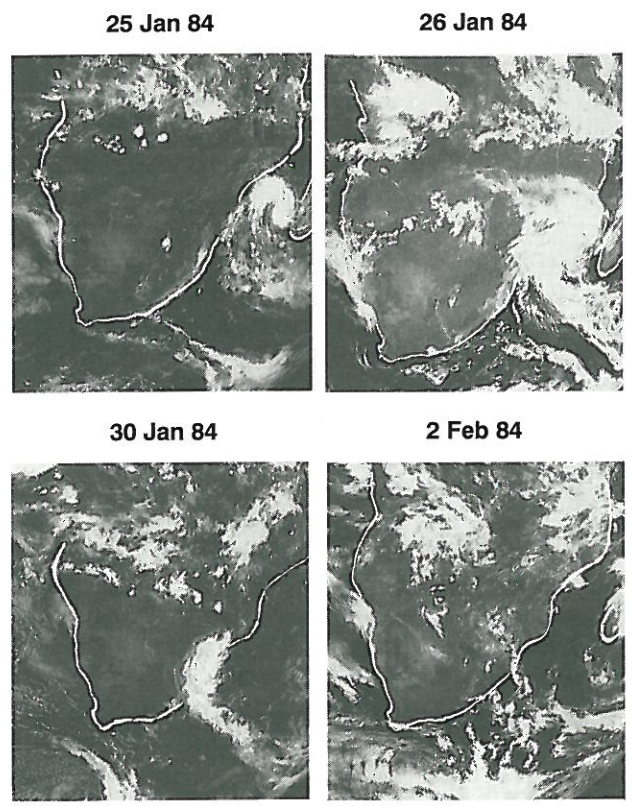


Winter weather pattern

towards the west. In winter, the inversion layer drops to a level which is below the eastern highlands of the escarpment, thus inhibiting moist air from the Indian Ocean from initiating rain in the interior.

The main sources of rain in the winter rainfall region are the cold fronts which approach the country from the west and south-west when the south Atlantic





Satellite images of cyclone Domoina

From 27 January to 1 February 1984, tropical cyclone Domoina moved across southern Africa. For five days torrential rains fell over southern Mocambique, the eastern Transvaal lowveld, Swaziland and northern Natal. More than 200 persons died in the ensuing floods, which were the largest in living memory.

high shifts northwards in winter. In summer, the high deflects them to the south of the country.

In the year-round rainfall area, the mountain ranges along the southern coastline confine the rain and drizzle arising from small, low-pressure storm systems to the coastal belt, particularly in winter.

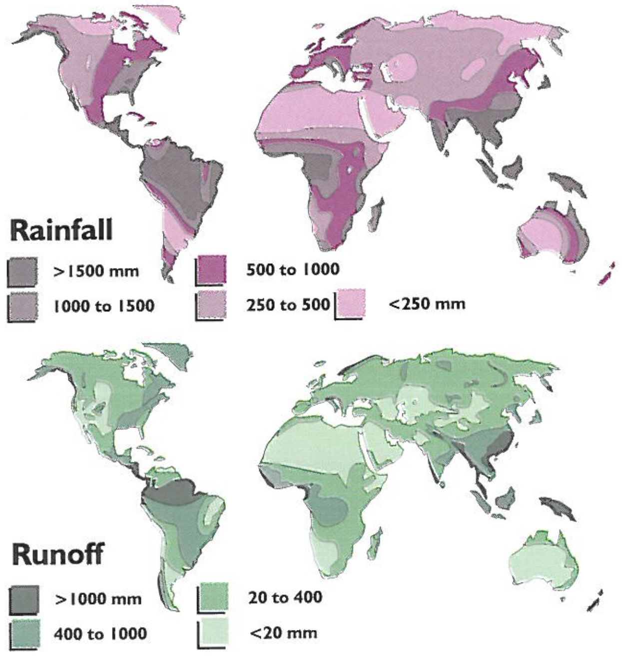
Rainfall distribution and variability

The average annual rainfall of South Africa as a whole is only 500 mm, compared to a world average of 860 mm. The humid subtropical conditions in the east and dry desert conditions in the west result in an uneven distribution of rain across the country.

Most of the rain falls in the marginal zone along the eastern and southern coastlines. So, for instance, the mean annual rainfall on the east coast in the vicinity of Durban is 1070 mm, while that for Port Nolloth at the same latitude on the west coast is a mere 60 mm. The highest rainfall occurs in the mountain ranges of the south-western Cape and in the Drakensberg, where the mean annual rainfall exceeds 3000 mm in places. Sixty-five per cent of the country receives less than 500 mm of rain annually — which is generally regarded as the minimum for successful rain-fed agriculture.

As it gets drier towards the west, the variability of the rainfall increases rapidly. The reliability and variability of rainfall across the country depends on how it is initiated.

Convectional storms can occur where land surfaces become very hot. Frequently violent and accompanied by thunder, lightning and hail, they cause most of the rain over the greater part of the summer rainfall region. Short, occasional convectional thunderstorms over small areas are also the main source of rain in the drier areas. If they are sufficiently intense, they may cause short-term flow in local streams.

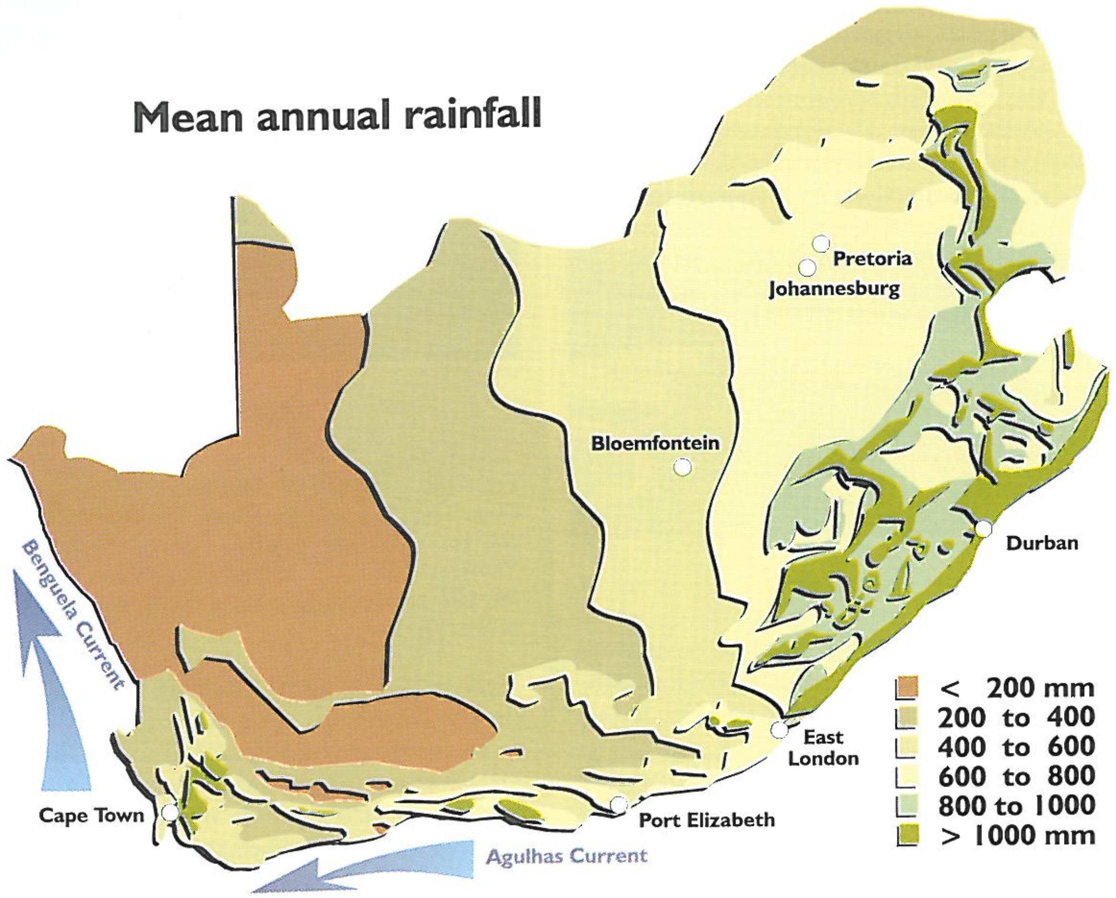


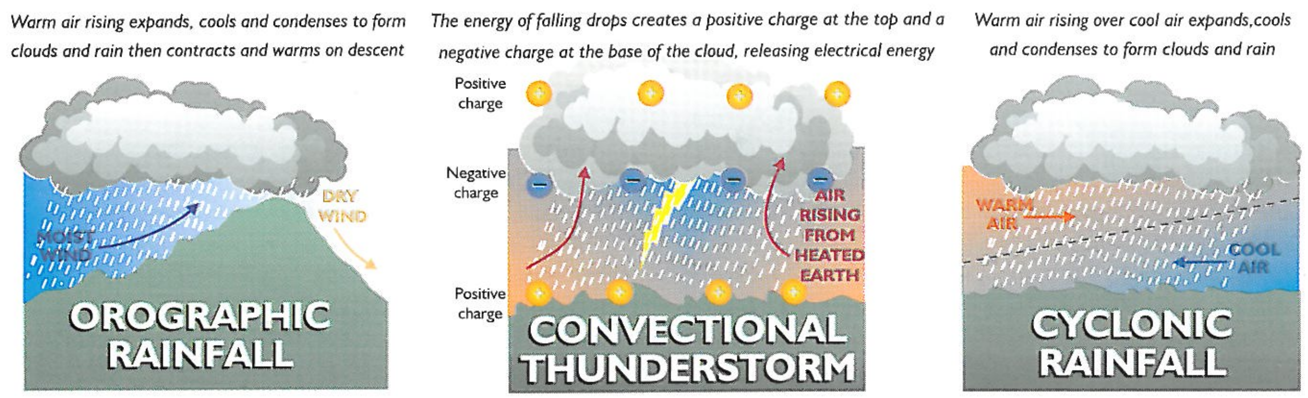
Simplified world average annual rainfall versus runoff

Orographic or *relief rain,* which originates from moist air that is blown up a mountain slope, is dominant along the eastern and southern marginal regions. While yielding less water than other rainfall mechanisms, orographic rain is more frequent and lasts longer, so that rivers in these areas tend to be more stable than those without a large orographic component. The rearward, or rain shadow, areas of these mountains receive far less rain than the windward slopes.

Cyclonic or *depression disturbances* can cause rain when large masses of warm air are forced up over large masses of colder air. This mechanism causes most of the rain in the winter rainfall region. The rain is often light and prolonged, except along the mountains, where orographic effects may induce heavy showers.

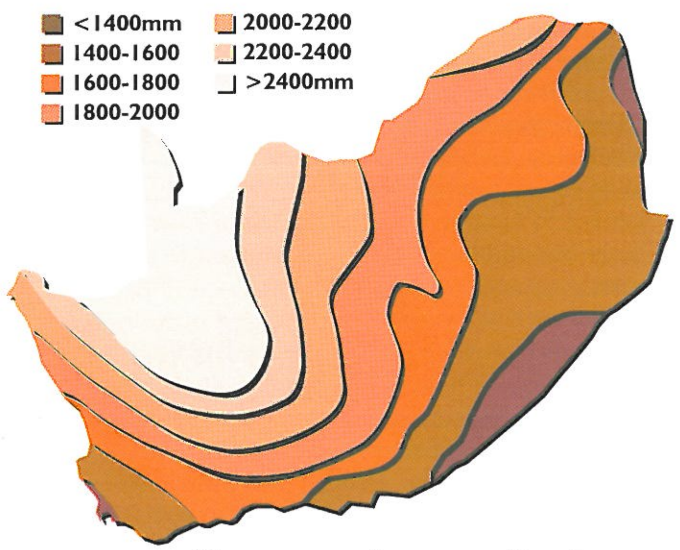
Snow contributes little to runoff as it may occur only briefly during the winter and melts within a few days.





Evaporation

Sunshine is abundant and cloud cover is meagre over much of South Africa. Consequently, the average annual potential evaporation is higher than the average annual rainfall in all but a few isolated areas, where the annual rainfall generally exceeds 1500 mm. Over the rest of the country the average annual potential evaporation varies from less than 1100 mm to more than 3000 mm per year. In the north-western Cape the potential evaporation is 25 times higher than the rainfall. Therefore, the difficulties of developing water resources under conditions of decreasing rainfall towards the west are intensified by the rising potential evaporation losses. In South Africa, the loss of water by evaporation is a very important consideration in the selection of dam sites and in the operation of water supply systems.



Mean annual evaporation from an open water surface

Because of the variability and evaporation losses, only about 62% or 33 000 million m^3 of the mean annual runoff can be exploited economically with present methods. In addition, about 5 400 million m^3 per year may be obtainable from groundwater. Further supplies will have to come from re-use, desalination or the importation of water. A watching brief is also kept on developments in the realm of unconventional water sources. These include the possible use of icebergs, rainfall stimulation and the suppression of evaporation. Rainfall stimulation holds some promise in limited areas of South Africa.

RIVER SYSTEMS AND WATER AVAILABILITY

Surface runoff is the main water source in South Africa, notwithstanding the fact that on average only about 9% of the total rainfall reaches the rivers. The average annual runoff of South Africa's rivers is estimated at 53 500 million m^3. Some highly variable rivers can have up to 10 consecutive years of less than average flow.

The mean annual runoff in South Africa is not directly proportional to the mean annual rainfall. It reduces far more sharply than a reduction in rainfall because of the high evaporation losses. In low-rainfall areas the soil dries out to a great extent, so that much of the sparse rainfall is absorbed by the soil and evaporates without reaching the rivers. South Africa's poor water supply situation may worsen if unfavourable climatic changes should arise from global warming.

The Great Escarpment separates South African rivers into two groups, namely the plateau rivers and those of the marginal areas. The eastern marginal area, covering 13% of the area of South Africa, accounts for about 43% of the total runoff. This is derived from several short, steep rivers which rise on the slopes and flow directly to the Indian Ocean. The longer east-flowing rivers in the north, such as the Limpopo, the Komati, the Crocodile and the Olifants, rise on the interior plateau and have broken through the escarpment.

Most of the plateau is drained by the huge Orange River System which flows westwards to the Atlantic Ocean. Although its catchment area comprises 48% of the area of South Africa, it contributes only 22% or 12 057 million m^3 to the total mean annual runoff because the rainfall reduces towards the west where the evaporation is high. Its major tributaries are the Caledon River and the Vaal River. Downstream of its confluence with the Vaal, there is almost no addition to its runoff over a distance of 1200 km. No water is known to have reached this reach of river from the large Molopo-Nossob system situated to the north-west.

In the south-western Cape the major rivers are the Gamtoos, Gouritz, Breede, Berg and Olifants, progressing westwards from the year-round rainfall area to the winter rainfall area.

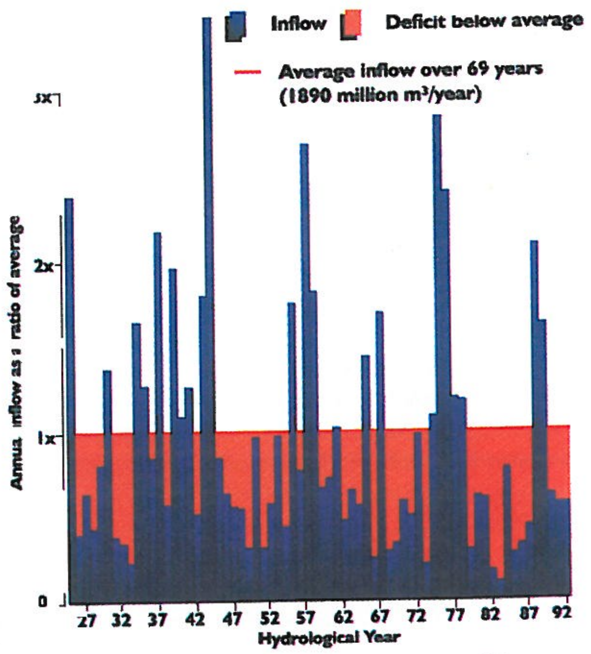
Only one-quarter of South Africa has perennial rivers. These are mainly in the southern and south-western Cape and on the eastern marginal slopes. With no inland lakes and permanent snows to stabilise flow, even these rivers flow irregularly and they are often strongly seasonal. Rivers that flow only periodically are found in a further quarter of the country. Over the entire western interior, rivers are episodic and flow only after infrequent storms.

Storage is generally necessary to be able to make the best use of runoff. The major dams in South Africa have a combined capacity of 50% of the total mean annual runoff. These dams command virtually all the runoff from the interior plateau. The practicable exploitation of the water sources of most of the interior part of the country has therefore been achieved.

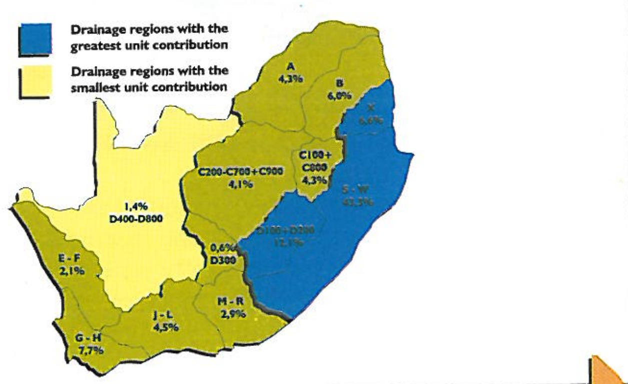
The undeveloped resources are mainly along the coast. However, it is now accepted that natural processes occurring in rivers, wetlands and estuaries require a share in the water resources of the country. Therefore, apart from the engineering constraints associated with developing steep coastal rivers, their exploitation may also harm sensitive estuaries. The need to retain some features of natural river flow to maintain in-stream processes requires streamflow hydrology to be evaluated in terms of its role in nature conservation. Therefore, the effect of seasonal variations and periodic events such as floods and droughts on natural processes is being taken into account in dam engineering to an increasing degree. The potential of these streams for urban, industrial and agricultural use may thus be reduced by a growing concern about the value of water for other purposes such as environmental conservation and recreation.

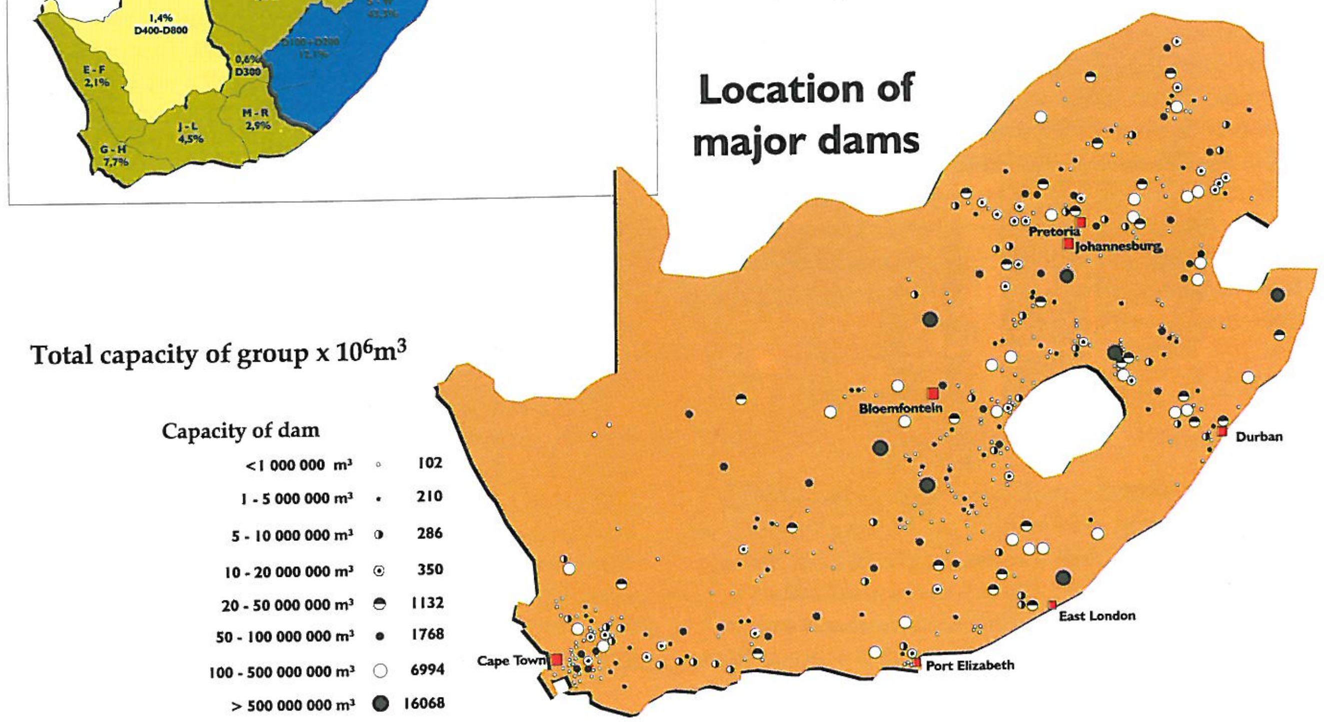
In accordance with the law of diminishing returns, the more a river is developed, the lower the yield will be of each equal increment of storage. This natural limit to what can be achieved merely by increasing storage

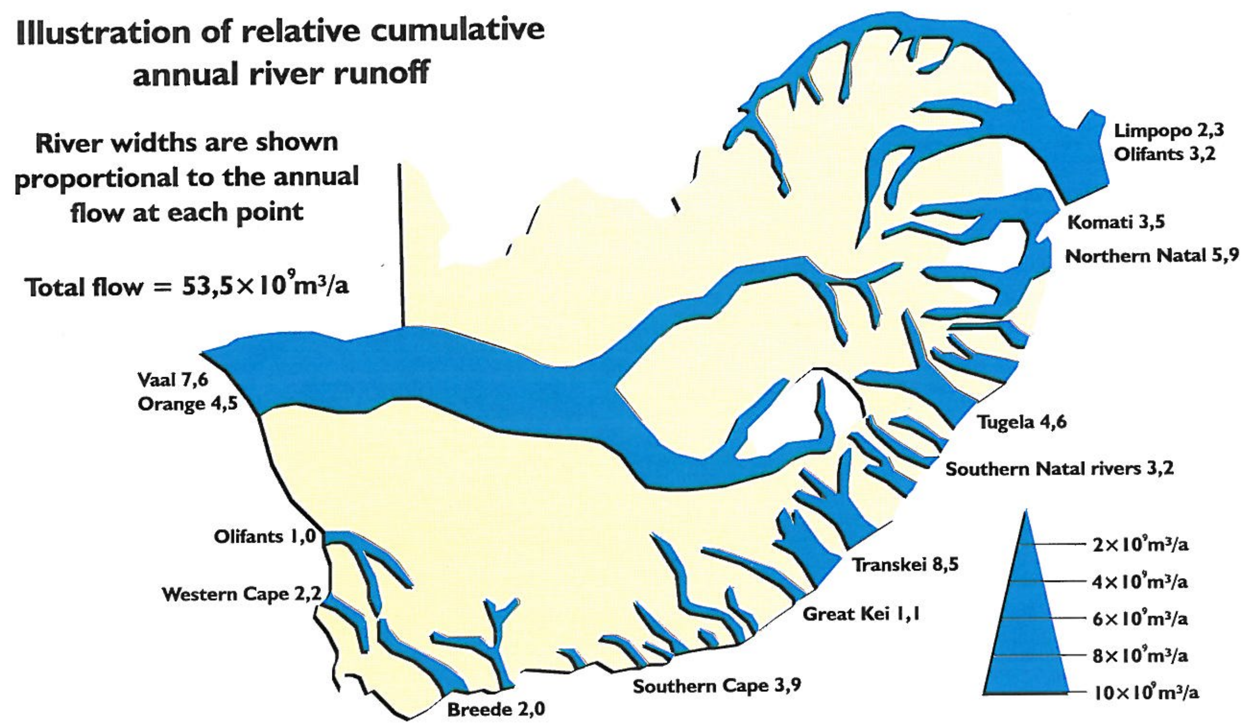
Illustration of flow variability

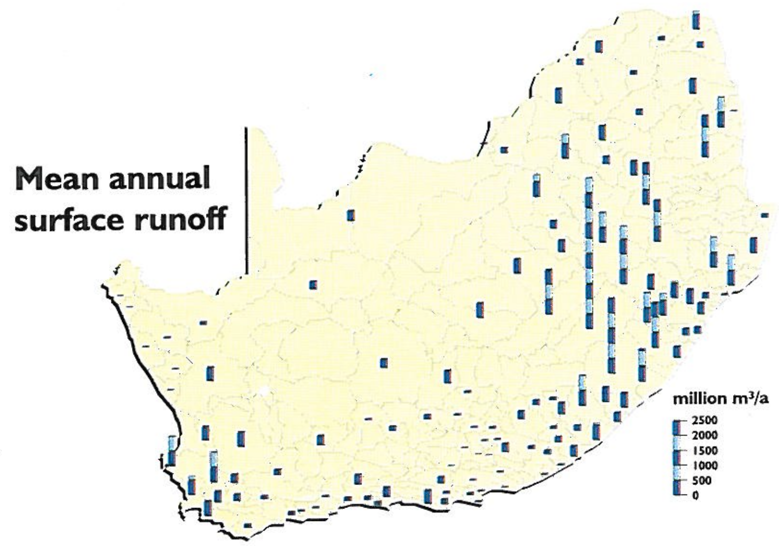


Annual flows in the Vaal River at the Vaal Dam. Including the catchment of the Grootdraai Dam

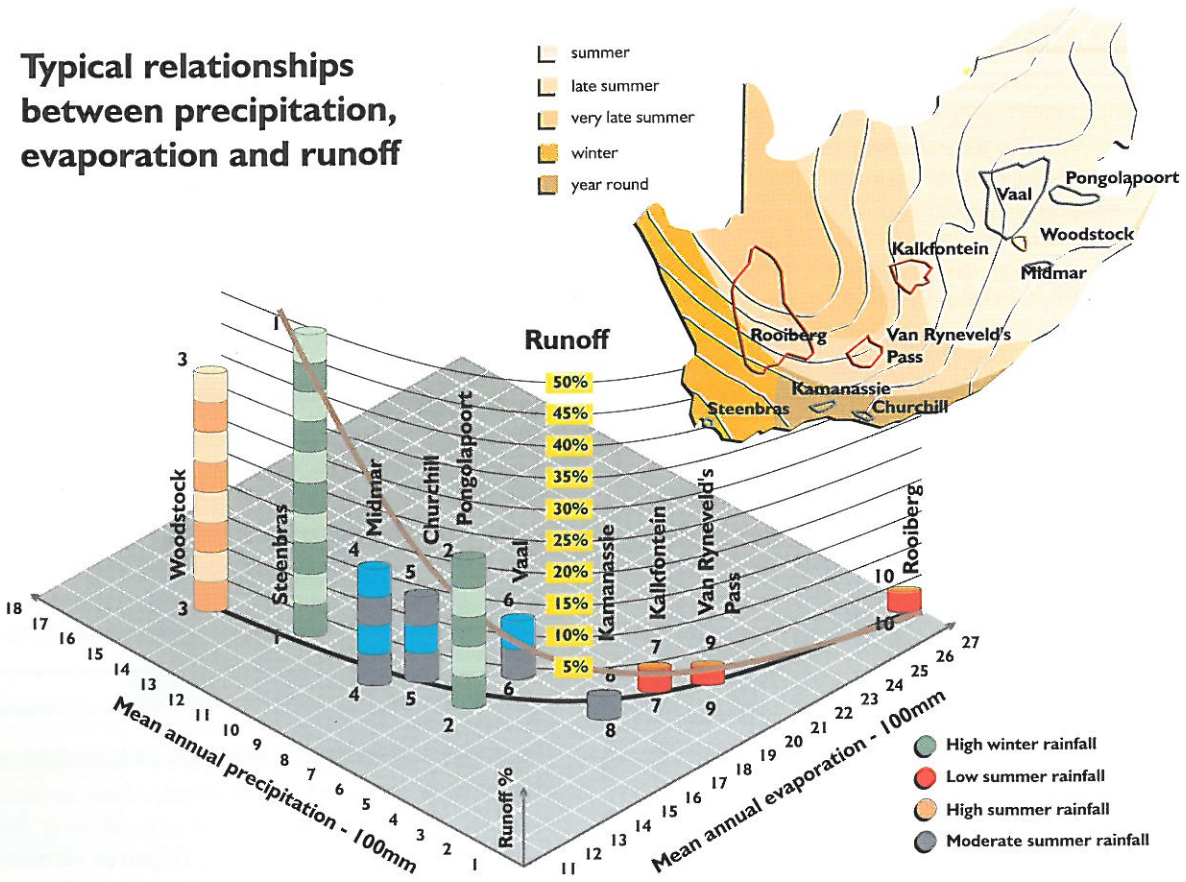








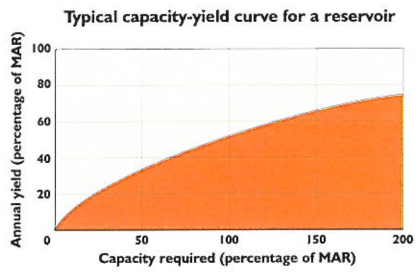
Typical relationships between precipitation, evaporation and runoff



Dam	Location and types of runoff-producing rainfall	Catchment area (km²)	Mean annual potential evaporation (mm)	Mean annual catchment precipitation (mm)	Mean annual runoff (mm)	Percentage runoff (mm)
Steenbras	South-western Cape: High winter rainfall, mainly orographic and frontal	67	1 413	1 231	619	50,3
Churchill	Southern Cape: High year-round rainfall, mainly orographic and frontal	357	1 390	740	202	27,3
Woodstock	Drakensberg: High summer rainfall, orographic and convectional	1 149	1 301	1 490	635	42,6
Midmar	Natal Midlands: Moderate summer rainfall in mist belt mainly convectional	928	1 386	975	198	20,3
Pongolapoort	Northern Natal: Moderate summer rainfall, mainly convectional with occasional tropical cyclones	7 831	1 514	871	140	16,1
Vaal	Highveld: Moderate summer rainfall, convergence and convectional	38 505	1 703	750	50	6,7
Kalkfontein	Orange Free State: Low summer rainfall, mainly convergence and convectional	10 268	1 874	452	15	3,3
Kamanassie	Little Karoo: In rain shadow, year-round low rainfall	1 505	1 697	463	24	5,2
Van Rhyneveld's Pass	Cape midlands: Low summer rainfall	3 681	1 996	365	10	2,7
Rooiberg	Great Karoo:Very low summer rainfall from occasional convergance systems	72 335	2 740	149	1	0,7

capacity points to the need for careful land management in the watershed to optimise yields. The building of farm dams severely reduces the runoff in some catchments, particularly during and after a prolonged drought and at the start of a rainy season. Long-term runoff reductions of the order of 40% have occurred in tributaries of the Orange and Upper Breede Rivers. Accordingly, greater attention is being paid to the catchment areas themselves, which have to be managed according to sound principles of environmental management and scarce resource allocation.

Typical capacity-yield curve for a reservoir

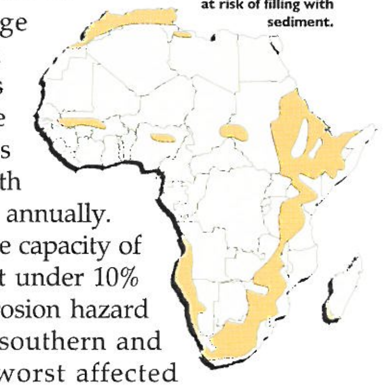


In general, the cost of providing dams in most of South Africa is higher than in many other countries because of the higher storage capacities required on South African rivers to achieve equivalent yields. This unfortunate natural handicap derives from the hydrological characteristics of our rivers. For example, the Vaal River, which supplies water to the economic heartland of the country, requires a storage capacity of 200% of the mean annual runoff to ensure a dependable gross yield of 75% of the mean annual runoff during a 1:50-year drought. An additional 10% to more than 100% storage capacity must be provided to allow for evaporation losses, depending on the dam basin characteristics and climatic conditions at a specific site. At the Vaal Dam it is 15%. To gain the maximum benefit from South Africa's limited runoff it is vitally important to use the most effective storage sites. Differing economic development patterns based on local circumstances have become established in the winter, summer and year-round rainfall areas. As the overall runoff is poorly distributed relative to areas experiencing economic growth, an increasing degree of territorial redistribution is needed at rapidly rising costs.

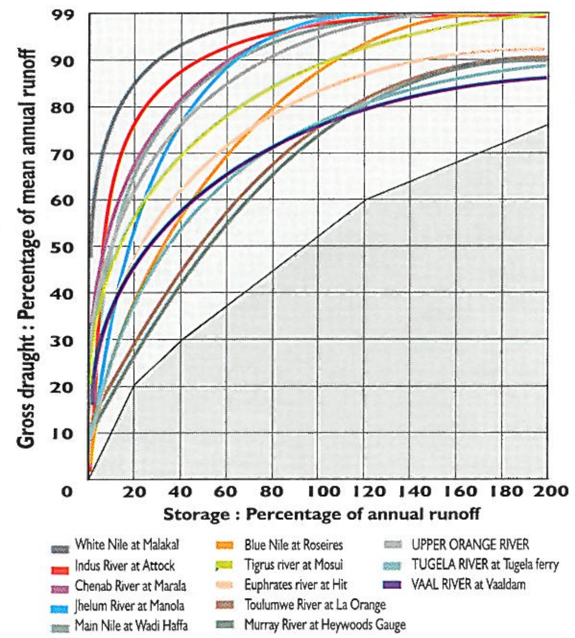
SEDIMENTATION

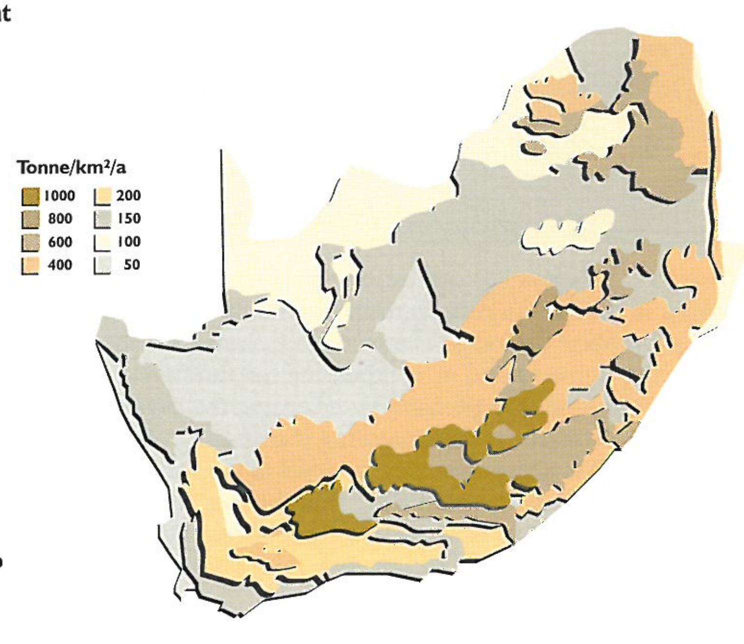
South Africa suffers from serious erosion of its soil and the consequent sedimentation of its reservoirs. In many areas, natural geological erosion has been accelerated by inappropriate land use. As is shown, the yield of sediment from large catchments is as high as 1000 t/km²/a. It is estimated that more than 120 million tons of sediment enter South African river systems annually. The average loss in the capacity of large reservoirs is just under 10% per decade in high erosion hazard regions such as the southern and eastern Cape. The worst affected reservoir has been the Welbedacht Dam near Bloemfontein, which experienced the sedimentation of 82% of its capacity within 19 years. This represents a loss of 4,3% per year. No economically viable methods for removing the sediment from South African reservoirs have yet been devised.

Zones where reservoirs are at risk of filling with sediment.



Draught curves of representative rivers for different countries (50-year recurrence interval)





Generalized sediment production map

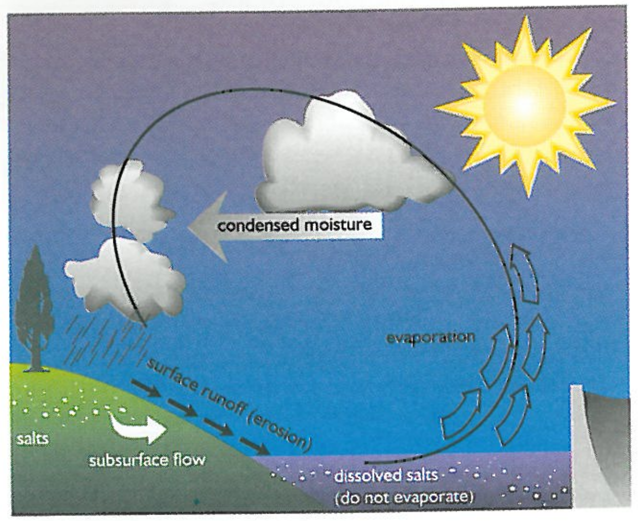
DECLINING WATER QUALITY

The quality of the water in many areas of South Africa is declining, primarily as a result of salination, eutrophication and pollution by trace metals, micropollutants and bacteria. Purposeful management of the water quality is aimed at ensuring its continued fitness for human, agricultural, industrial and recreational use, as well as for the propagation of the fish, wildlife and plant species that could reasonably be expected in a particular environment.

As South Africa is water-deficient, effluents have to be purified and returned to the watercourses. With growing industrialisation, urbanisation, irrigation and the use of artificial fertilisers and pesticides, the quality of the receiving waters is being lowered by the return flows. In time, poor quality may become more critical than reduced availability in some areas, particularly in the interior of the country.

Salination

Salts leached from the products of geological weathering in the watersheds accumulate in reservoirs with other salts released from the soil by farming and soil



erosion. Evaporation can increase the salt concentrations in reservoirs considerably, particularly under long retention periods. The raising of dams to meet growing demand and to compensate for sedimentation compounds the problem by enlarging the evaporative surface area and diminishing the flushing effect of floods. Thus, the mean salinity level of the water in the reservoirs rises gradually. The higher salinity restricts the number of cycles of industrial reuse which are practicable, requiring a greater amount of water to compensate for its poorer quality.

When the water is used for irrigation, the dissolved salts are concentrated in the soil by evaporation and evapotranspiration. If they are not leached or flushed out, the soil salinity may rise to a level at which the lands go out of production. It is therefore necessary to meet increasing requirements for leaching and to reduce downstream salinity. As South Africa will not always have enough water for flushing, researchers are seeking ways of intercepting and re-using irrigation drainage water. Mathematical models are also being developed to improve irrigation management at regional and farm levels. For instance, a cell-based model in which water retention, application, crop-water use, salinity, soil percolation and evapotranspiration processes are simulated daily is leading to a better understanding of rootzone dynamics, groundwater movement, catchment hydrology, riverflow regulation and optimum irrigation practice.

Problems arising from the use of a watercourse both as a freshwater supply channel as well as a return-flow drain are common to many South African rivers. Owing to the high cost of canals, as well as for environmental reasons, the use of many river channels for the supply of water will have to continue. Some solutions to these problems may lie in the interception, diversion, re-use and disposal of return flows. However, as all return flows, such as groundwater seepage, cannot be intercepted, it is necessary to increase the levels of skill required to operate river systems and reservoirs in such a way as to counteract the harmful impact of return flows.

Eutrophication

Eutrophication, or the enrichment of water with nutrients, is a natural process which is intensified by urbanisation, agriculture and industry. Soluble nutrients such as phosphates and nitrates in effluent promote excessive increases in algae and other aquatic plants in watercourses and reservoirs, reducing the degree of fitness of the water for many uses. Purification and supply costs increase because canal capacities are reduced, filters are clogged, increased chemical dosages are necessary and special treatments are required to remove tastes and odours. Carcinogenic (causing cancer) trihalomethanes may be formed when water from eutrophied sources is chlorinated during purification. Toxins produced by

certain species of algae such as *microcystis* may kill livestock and fish and harm human beings. In addition, water surfaces become unattractive, water sports are hampered and lakeside properties lose market

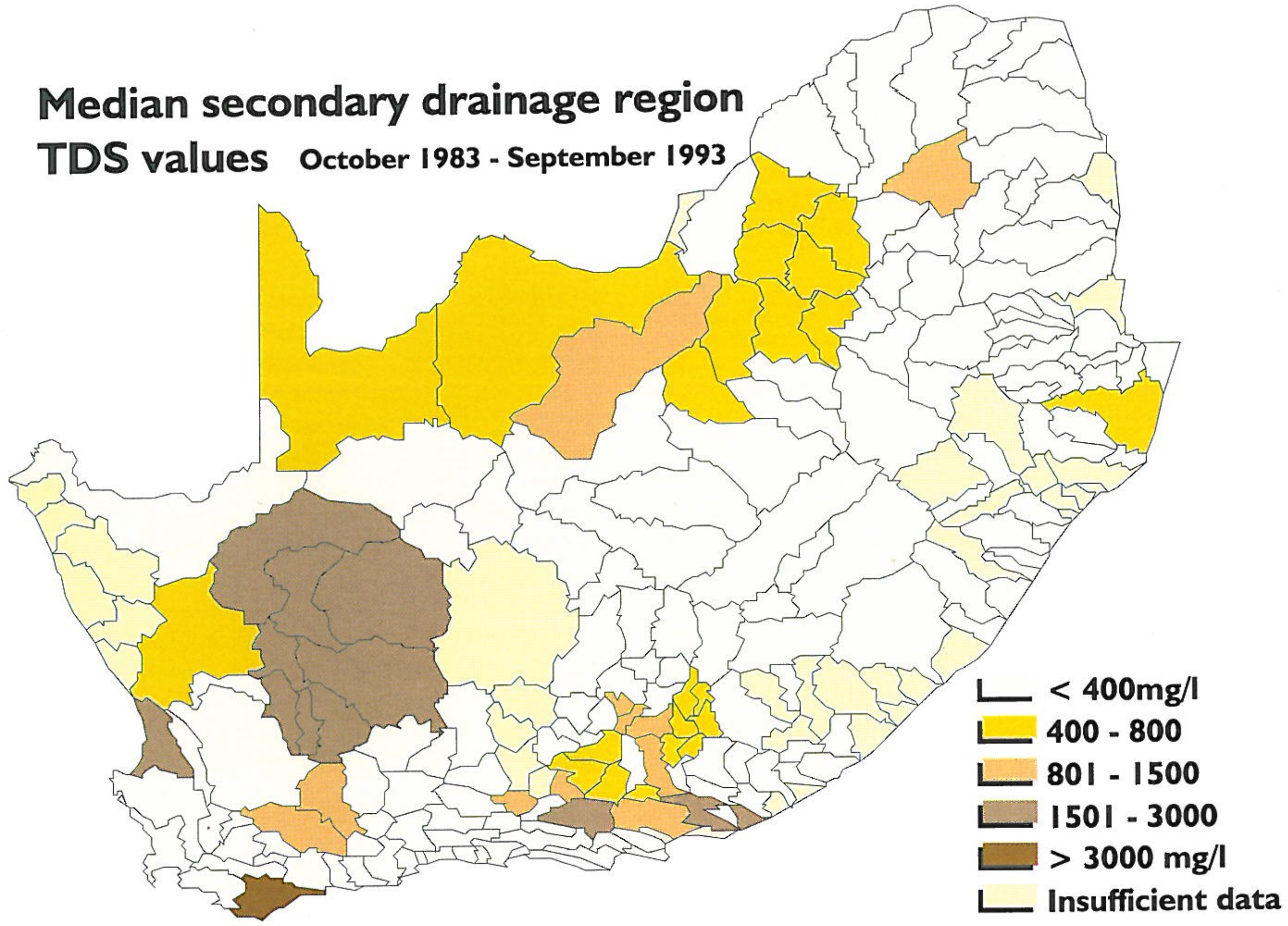
Fish killed by toxins

value. The deoxygenation of the deeper zones of reservoirs by the decomposition of algae and water plants may also disturb biological activity and reduce the range of species of desirable fish. Some dams in South Africa are provided with outlets at various depths to enable the best quality of water to be drawn off and to reduce treatment costs.

Trace metals, micropollutants and bacteria

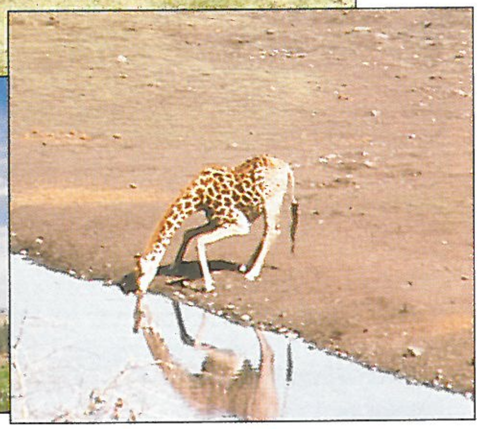
Water sources in South Africa are also being contaminated by trace metals and micropollutants. Organic and metal compounds enter surface and underground water through effluent discharges, leachate from solid-waste disposal sites, agricultural and urban runoff and atmospheric fallout. Many of these compounds resist physical, chemical and biological degradation and persist in the environment. Toxic, carcinogenic, mutagenic (producing genetic changes) or teratogenic (causing prenatal defects) contaminants can become hazardous, particularly during low flows. In addition, the growth of informal settlements without adequate sanitation systems increases the risk of transmitting waterborne diseases.

Strict controls are being imposed on point source pollution. Methods are also being devised to deal with diffuse pollution, so as to reduce the presence of contaminants in water, in sediment and in the biota of aquatic ecosystems. In addition, stringent operating rules are being developed for river systems to deal with residual pollution that cannot be directly controlled. These include the electronic monitoring of water quality in river reaches to control blending techniques, employing precisely timed reservoir releases.



OVERCOMING THE DIFFICULTIES POSED BY SOUTH AFRICA'S INADEQUATE WATER SUPPLY

Relative to the growing demand, water is scarce in some areas of the country and it is expected to become scarce in most areas. Unexpectedly, it can become scarce anywhere during droughts.



Demands for water range from those which cater for the material needs of people by supporting life, hygiene, domestic use, agriculture and industry, to those which provide spiritual gratification by conserving and beautifying the environment and supporting recreation. While the water needs of the large developing sector are increasing rapidly, the developed economy is becoming more reliant on an improved assurance of supply and the maintenance of an adequate water quality. The proportion of the total required by users who need a high assurance of supply, such as the power-generating, municipal, domestic and industrial sectors, is also increasing. To be viable, modern power-stations, mines, industries, sanitation systems and capital-intensive irrigation equipment cannot conveniently accommodate cutbacks. Unfortunately the substitution of other factors of production, such as capital, to compensate for the relative scarcity of water, is only viable if the assurance of the water supply can be improved. Therefore, getting to understand the implications of supply risks which depend on the vagaries of the weather is becoming very important for the operation of schemes and as a basis for investment decisions.

Serious conflicts among water users are escalating as the demand for water outstrips its regional availability. Therefore, the extent to which South Africa can continue to reconcile demand with supply depends on how adaptively the water resources can be managed. In addition to building more dams, great benefit can be gained from water management techniques aimed at the better use of existing works. Also, new electronic information systems incorporating hydrological models and econometric concepts are being developed to assist with the optimal management of entire drainage basins. Earlier in the century the emphasis was on the construction of single-purpose dams, mostly to promote irrigation. It had not yet become necessary to optimise the combined operation of several dams and conduits as regional systems to supply multiple user groups. It is now no longer possible to safeguard the country against droughts merely by building more dams. New works require very large capital investments and, in many cases, international co-operation. Many classes of user cannot afford the costs. The creation of unwarranted reservoirs ahead of demand also ties up capital, imposes a burden of accumulating interest charges, and raises the salinity of the stored water and the rate of sediment accumulation in the basins. Improvements to the timing of construction phases are being achieved by monitoring the statistical chance of shortfalls from existing works and by evaluating the different implications of rationing on each of the user sectors. Overall, this implies the continuous refinement of public expenditure and construction programmes for financial, economic and socio-economic effectiveness. The purposeful management of demand also requires the use of incentives to induce users to make better use of water.

In the future, it will be necessary to continually rank trade-offs between alternative opportunities for using water. Also, methods of distributing the gains and losses which are regarded as the fairest by the various contenders must be continually improved. Ideally, South Africa should be able to manage its water in a manner that takes full account of the entire

hydrological cycle, with as good an understanding as is practicable of hydrological processes such as condensation, rainfall, evaporation, infiltration, seepage, runoff and erosion, as well as of the value of each alternative use of water at each site and the detriment in being unable to meet it.

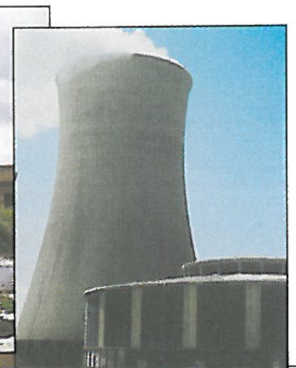
A good partnership between water managers and a well-informed public is becoming more necessary as conflicts increase. It is important to establish proponents to champion the cause of each user group and to mobilise their insights under informed peer pressure, to justify the allocation of water for consumptive and non-consumptive uses. For this reason, the development of communication forums is being encouraged.

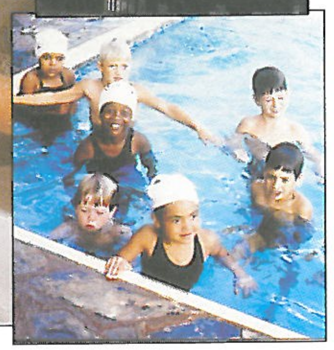
Planning must aim at achieving the most equitable overall benefit with the least individual detriment between geographic regions, between user sectors and between individual users. The excellence of reconciliation of demand, supply and quality that can be achieved will depend on the calibre and currency of information and the successful development of techniques to reliably portray the merits of trade-offs.

South African water management is also becoming more international in character. At this level, the trend is towards improved relations with our neighbour states and a growing realisation of the need to manage water on a subcontinental basis. The simple, rigid abstraction allocations which sufficed in the past under conditions of relative abundance cannot be sustained under increasing scarcity. The relative contributions and requirements of different portions of the watercourse system, based on a good understanding of the associated climate, are becoming important parameters for international negotiation.

A sustainable management strategy aims at ensuring the indefinite availability of adequate quantities and qualities of water for all competing user groups at acceptable costs and assurances of supply under changing conditions. To achieve this, it is necessary to maintain an optimum dynamic balance between the management of supply, demand and quality. This can be done by the expansion of an affordable bulk supply infrastructure consisting of regional, interregional and international waterworks, as well as by catchment, groundwater and effluent management and the maintenance of integrated controls over water allocation, use and disposal.

To achieve such a daunting goal requires the evolution of more comprehensive systems of dams and distribution works, which will have to be operated using state-of-the-art techniques. It also requires an improved understanding of all the hydrological processes that occur in drainage basins, so that they may be taken into account within the context of integrated watershed and environmental management.





REFERENCES

Bunnett RB (1981). *Physical Geography in Diagrams.* Longman

Byers HRB (1959). *General Meteorology.* New York, McGraw-Hill Book Company

Earle JL, et al. (1986). *New Window on the World.* Cape Town, Juta and Co

Petersen MS (1993). *Water for Africa.* Symposium Proceedings: Water the Lifeblood of Africa.Zimbabwe, International Association for Hydraulic Research

Reader's Digest Atlas of Southern Africa (1984). Cape Town, Reader's Digest Association South Africa

Riehl H (1972). *Introduction to the Atmosphere.* New York, McGraw-Hill

Schultz BR (1984). *Climate of South Africa, Part 8, General Survey.* Weather Bureau, South Africa, Department of Transport. Pretoria

Scotney DM, Volschenk JE and Van Heerden PS (1990). *The Potential and Utilisation of the Natural Agricultural Resources of South Africa.* South Africa, Department of Agricultural Development. Pretoria

South Africa, Department of Water Affairs (1985). *Documentation of the 1984 Domoina Floods. Report TR 122.* Pretoria

South Africa, Department of Water Affairs (1986). *Management of the Water Resources of the Republic of South Africa.* Pretoria

South Africa, Department of Water Affairs and Forestry (1991). *Water Quality Management Policies and Strategies in the RSA.* Pretoria

South Africa, SA Communication Service (1993). South Africa 1993. *Official Yearbook of the Republic of South Africa.* Nineteenth edition and previous annual editions. Pretoria

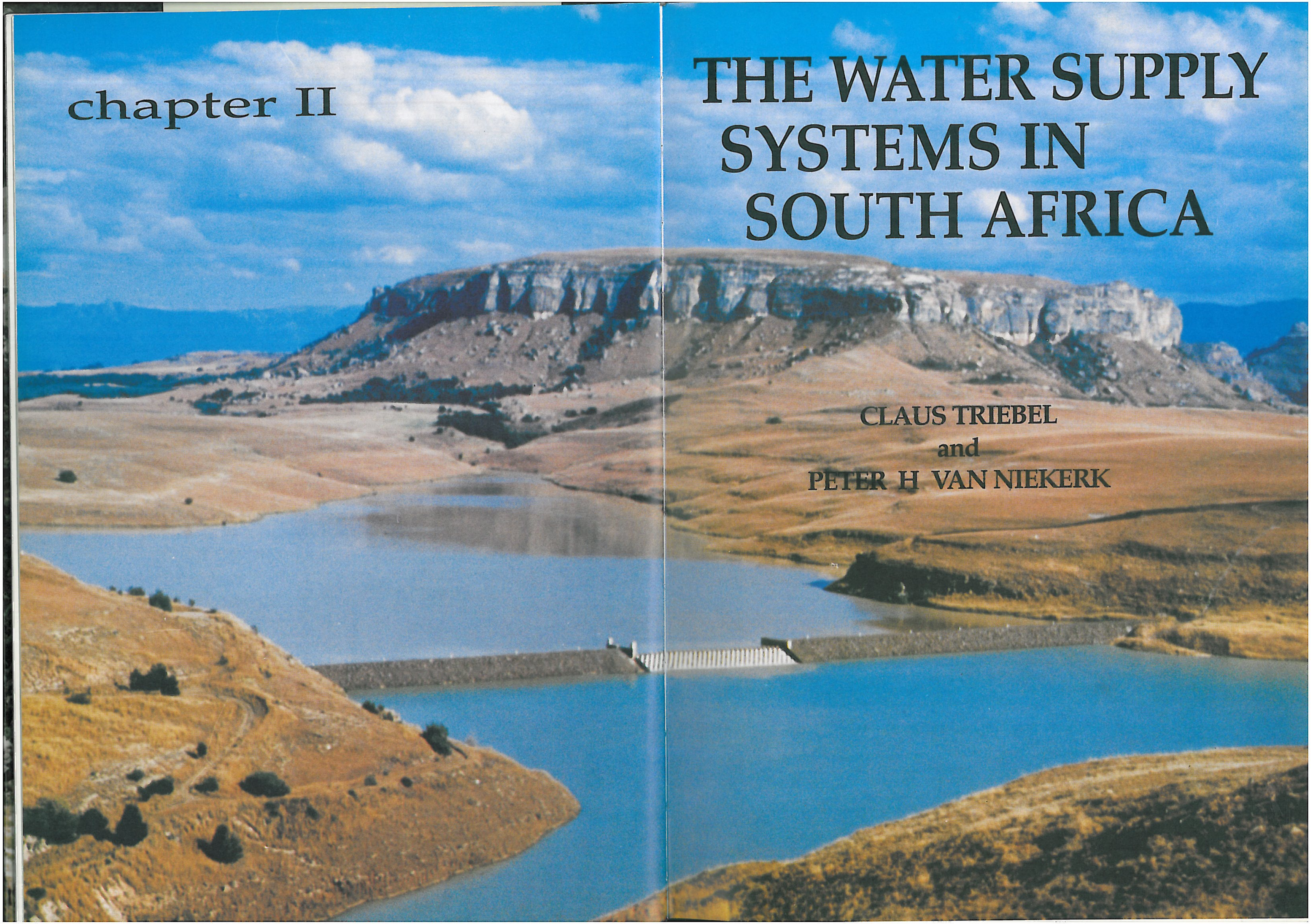
The Times Concise Atlas of the World. (1967) London, Times Books

Ward RC and Robinson M (1988). *Principles of Hydrology,* Third ed. New York, Mc Graw-Hill

chapter II

THE WATER SUPPLY SYSTEMS IN SOUTH AFRICA

CLAUS TRIEBEL
and
PETER H VAN NIEKERK



THE WATER SUPPLY SYSTEMS IN SOUTH AFRICA

by Claus Triebel and Peter H van Niekerk

A review of the history and present status of dam engineering in South Africa must take cognisance of the water availability in the region and the water supply systems that have been developed. This book proposes to bring the reader up to date regarding not only the dams of South Africa, but also the water supply systems in which these dams function — either singly, in series, or in parallel. The main rivers and their catchments are intimately interwoven with the country-wide water supply network, intercatchment water transfer schemes and international water commissions and joint projects. These have evolved over the last decades within the Republic of South Africa as well as across the borders with its neighbouring countries. The main water supply projects are shown in Figure 1 and are listed, together with their main components: dams, tunnels, canals and pipelines, in Table 1. These are operated by the Department of Water Affairs and Forestry and a number of Water Boards listed in Table 2. A few of these will be described in later chapters of this book. (The technical data on large dams in South Africa is contained in Chapter XI).

Physiography and meteorology

The significance of dams in supplying the water needs in the country and the reasons for the development of integrated supply systems are found in the physiography and meteorology of the land. As described in Chapter I, the climate varies from subtropical on the eastern seaboard to arid on the western side. The intercontinental divide is formed mainly by the Drakensberg escarpment running north-south and draining eastwards to the Indian Ocean and westwards to the Atlantic, and dividing the country by approximately one-fifth to the east and three-fifths to the west, while the remaining one-fifth drains south from the east-west dividing ranges separating the Great Karoo, or inland basin, from the coastal basins. East and south of these two escarpments the climate is temperate and to the west it is semi-arid to arid.

Growth and development

Formal agricultural development started in the Western Cape and followed the generally more favourable climatic conditions in an eastward direction, while mining (diamond and gold) in the nineteenth and early twentieth centuries attracted development in a more northerly direction. This was followed by industrial development with concomitant location of large numbers of people in the region roughly demarcated by the Witwatersrand (Johannesburg), Pretoria (the capital) and Vereeniging on the banks of the Vaal River — today known as the PWV area — the major population concentration in the country. On the coalfields of the Northern Free State and the South-Eastern Transvaal Highveld followed oil-from-coal production plants, Sasol I, II and III, as well as a number of Eskom thermal power-stations.

Distributed over the Southern Transvaal, Northern Free State and Northern KwaZuluNatal, in close proximity to coalfields, Eskom built thermal power-stations with generating capacity now totalling 30 000 MW. All these developments necessitated the construction of water schemes; first single, then multiple-purpose dams, and ultimately transfer schemes from adjoining or even remote catchments.

Parallel to the industrial growth, agricultural development surged ahead: a number of large irrigation schemes were developed, such as the Vaalharts, the Crocodile River (Western Transvaal), the Loskop (Olifants River), the Pongola, and the Orange River Project with, amongst others, its link to the Eastern Cape (Fish-Sundays River scheme). Numerous smaller irrigation projects were developed in the Western Cape, the Orange Free State, Natal and Transvaal, many of which were supplied from reservoirs created by dams on the principal rivers.

Interbasin transfers

Rainfall and runoff vary greatly in Southern Africa; not only geographically, but also from one year to the next. Similarly, the mineral and fossil fuel deposits on which development was founded are unevenly distributed and often located at great distances from water resources. This has led to the building of interbasin transfers, as shown in Figure 1, involving large dams and long conveyance structures.

The planning of water resources moved away from solving single supply problems to finding solutions for regional water supply requirements, thus necessitating planning on catchment, and sometimes multiple catchment, bases. Concepts of interbasin sharing, international apportionment (where applicable) and conflict resolution between interested and affected sectors progressively became more and more applicable to water resource management in Southern Africa. Similarly, the operation of the water supply systems became more complex, necessitating highly sophisticated approaches.

In the following sections these developments will be further expanded upon, starting with a historical overview and the development of the Algoa System as an example and ending with the development of the Vaal River System.

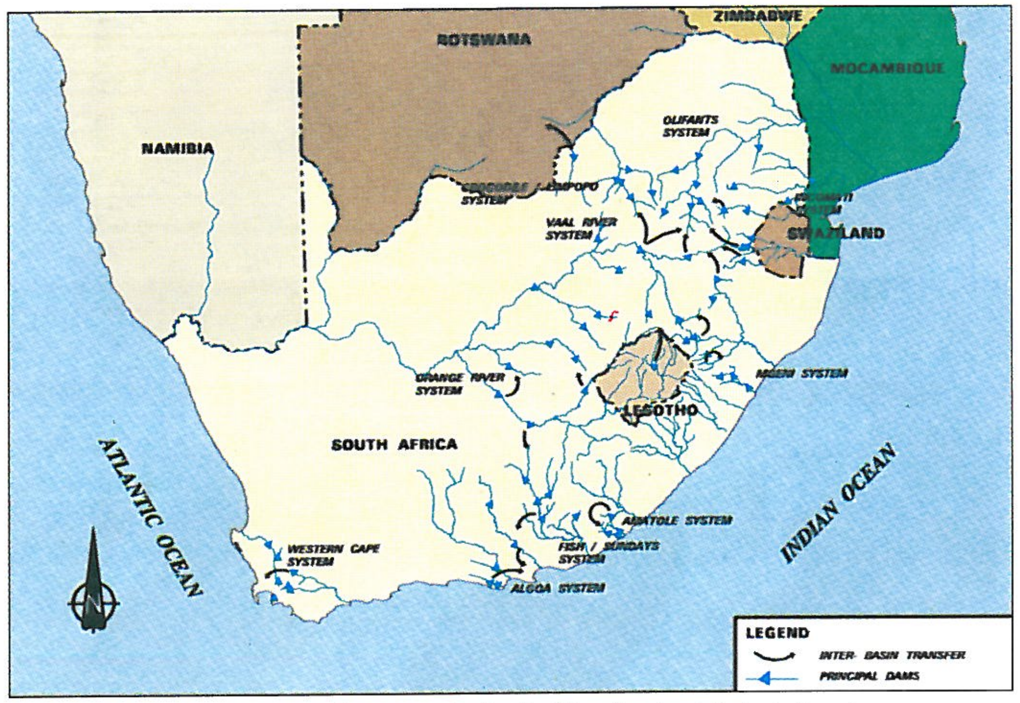


Figure 1: Water supply systems in South Africa showing interbasin transfers

EARLY WATER SUPPLY DEVELOPMENT IN SOUTH AFRICA

Early historical communities in South Africa settled within accessible distances from perennial streams or springs. The changeable climate, however, often dried up these sources, forcing the communities to relocate, which resulted in conflicts with neighbouring communities. It was only during the last century that communities came to rely more on communal schemes to extend their supplies. The earliest water storage work on record is the Waegenaars Dam built by the Dutch East India Company in Cape Town in 1663. It stored 2 000 m^3 of water for the supply of passing ships.

The Eastern Cape, however, in subsequent years saw far more water-engineering activity, brought on by the severe droughts that afflicted that part of the country at fairly frequent intervals. It is instructive to examine, as an example, the evolution of one of the pioneer schemes — that of water supply to the town of Port Elizabeth in the early days.

Water supply to Port Elizabeth: a historical example

In 1848 the Commissioners of the Municipality of Port Elizabeth asked for a tender to sink a public well *5 feet in diameter, and to hold no less than 6 feet of water.* As far as can be ascertained this was the first communal water work undertaken by the Municipality. The well was duly completed in 1850, and was soon followed by the construction of a number of additional wells. These were not adequate to cope with the increasing demand of a fast-growing town at the time. In 1863 a masonry dam, the Frames Dam, was completed in the Sharks River (now called Happy Valley) and the water was reticulated into the centre of the town. This was soon followed by the extremely severe drought of 1865 to 1866, which proved that the water supplies for the town were still inadequate. In addition, salinity problems arose with the water from the Frames Dam, and after protracted discussions with the Colonial Government, followed by a Bill in Parliament, an ambitious scheme to divert water from the upper reaches of the Van Stadens River to Port Elizabeth through a pipeline 45 km in length was completed in 1880. This was the first significant interbasin water transfer in South Africa.

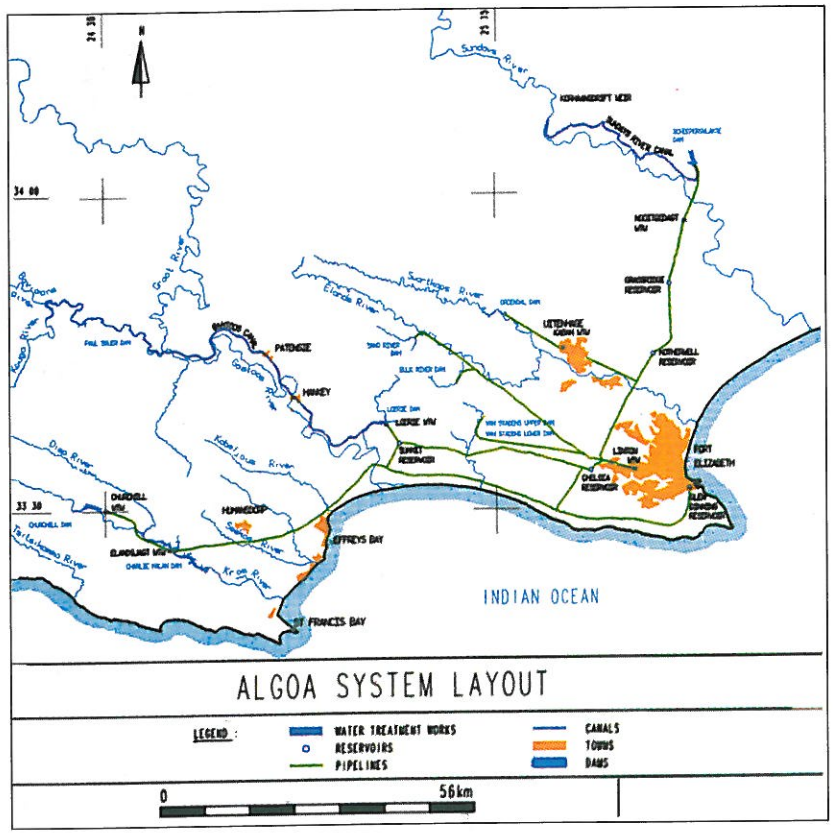


Figure 2: Algoa System layout (by courtesy of DWA&F and Ninham Shand, Inc.)

However, the run-of-river diversion of the Upper Van Stadens River soon proved to be unreliable. In 1893 the Upper Van Stadens Dam, 15 m high and with a storage capacity of 130 000 m^3, was completed above the intake of the pipeline. This was the first of a series of dams and aqueducts eventually to be constructed to supply Port Elizabeth and its environs with water. In 1903 and 1907 respectively, the Bulk River and Sand River Dams were constructed, followed by the Lower Van Stadens River Dam in 1929.

The Churchill Dam, which harnessed the Krom River, was completed in 1947, and in 1968 the City of Port Elizabeth was linked for water supply, via the Loerie Dam, to the Paul Sauer Dam, built by the then Department of Water Affairs on the Kougha River (primarily to supply irrigation water to the Gamtoos Valley). By 1985 the Department of Water Affairs had also completed the Charlie Malan Dam on the lower Krom River for further supplies to Port Elizabeth, and in 1992 the city was linked to the very large Orange River Project via the Sundays River. The entire system, as it is functioning today, is shown in Figure 2.

General evolvement of water supply from local to regional systems

The history of water supply to Port Elizabeth outlined above is also typical of the history of water supply development to many towns and cities in South Africa. Private water supplies were initially augmented by communal schemes. These were modest at first but were later followed by the construction of large dams and eventually the importation of water from neighbouring catchments. As the systems increased in size, the opportunity for lowering costs by combined, regional-based schemes improved. The Government, which had considerable experience in irrigation water supply, undertook to construct such schemes, and hence to regulate and apportion bulk water supplies. With the increasing demands of mining and industry the Government embarked on increasingly larger scale water supply schemes. Many of these Government water schemes later became interlinked to form large supply system networks. The Vaal River System is probably the most important of these today. This system is described in further detail in the last part of this chapter.

Another large interbasin water supply system in the country is the Orange River Project, which is now connected to the Vaal River System. Together these two extend over more than half the area of the country. The Western Cape, Algoa, Amatole, Mgeni, Olifants and Incomati Systems are other large interbasin transfer systems. These are depicted in Figure 1. Some of these projects are described in more detail in other chapters.

Operation of large water supply systems

The complexity of managing interlinked water supply systems has created the need for a more sophisticated methodology to support decisions on the optimal operation of these systems as well as their future expansion. Mathematical computer simulation tools have been developed to model the systems under a wide range of conditions. The uncertainty of climatic conditions has been taken into account to advise the South African water resource managers on how to deal with the risks involved. These developments represent an innovative and advanced technology and, as far as can be ascertained, South Africa is one of the leading countries in the operational employment of these techniques.

THE DEVELOPMENT OF WATER LEGISLATION IN SOUTH AFRICA AND ITS INFLUENCE ON WATER SUPPLY SYSTEMS

Parallel to the physical development of water supply systems, similar progress was made on the institutional and legal sides. South African Water Law has evolved from Roman Dutch Law as later modified by English Law. Originally the State, under Dutch rule and by Roman Dutch Law, exercised full control over the use of water in rivers and streams in the Cape Colony, but during the nineteenth century, under British rule, the exclusive right to the use of this water, by English Law, was given to riparian owners.

As the country developed over the centuries, and especially after the Second World War, this exclusive riparian right became incompatible with the growing needs of the industrial and other users in a basically water-deficient country. In 1950 a Commission of Enquiry into the Water Law of South Africa was appointed and its report led to the promulgation of the Water Act, 1956 (Act 54 of 1956). At the same time the name of the Department dealing with water was changed from the Department of Irrigation to the Department of Water Affairs, thereby more accurately reflecting its broadened responsibilities. The present development and management of water supply is in accordance with this (South African) Water Act.

State involvement in terms of the Water Act, 1956 manifests itself primarily in the following aspects:

1 *The construction of Government water works for the supply* of water for irrigation and other purposes on conditions determined by the State, but with due regard to existing rights that are being beneficially exercised. Major water schemes are capital intensive and usually only the State can finance schemes that fully exploit the potential of the larger rivers (Water Act, 1956, sections 56 (3) and 63).

2 *Control by permit over the use of public water* for industrial and urban purposes. Urban and industrial development contains the inherent risk of water pollution, unless precautionary measures are timeously taken. The high rate of such development, particularly over the last few decades, has caused the Government to be entrusted with a major task in the protection of water resources in the public interest (Water Act, 1956, sections 12, 13).

3 *The allocation of rights to the use of public water.* Apportionment of the water of a public stream by a water court proved to be a complex and expensive exercise and, in addition, no other consideration (apart from the riparian right principle) could be considered in an apportionment by the judiciary. The Act vests in the Minister of Water Affairs the authority to declare any defined area a Government Water Control Area, for the State to control the abstraction and use of public water within such area. In a Government water control area the State approaches its former position of *dominus fluminis*, but with a number of important qualifications that safeguard the rights of riparian owners (Water Act, 1956, section 62).

4 Outside Government Water Control Areas the *riparian rights principle* remains unaffected, except that *permits are required* from the State in terms of the Act for the construction of larger storage and diversion works (Water Act, 1956, section 9B).

5 *The local control*, which in the past had been exercised by irrigation boards, has been extended to urban and industrial users *by the introduction of water boards*, whose chief function is the provision of water in bulk mainly for urban and industrial use in their areas of jurisdiction. A recent further development, still to be implemented, is the extension of the function of water boards to include regional sewage schemes. Irrigation boards and water boards are under the broad supervisory control of the State.

Water rights and water law in the future

Throughout the world there is a tendency to centralise control over the allocation and exercise of rights to the use of water, especially in countries where the demand is approaching the level of availability. Although the South African Water Act, 1956 has afforded the State adequate powers to develop and control the country's water resources during the changing circumstances of the past 30 years, it has become apparent that further development of Water Law will be required to meet the challenges of the future. The most important areas in which further development of Water Law is required, are improved water quality management, the impact of water schemes on the environment, optimal allocation, ownership and use of water and the permanency thereof, improved abstraction control, land use impinging on water resources and extended jurisdiction for Water Courts.

National versus private initiative

Until 1875 the responsibility for water resource development — then primarily for irrigation — remained in the hands of private enterprise and village and town authorities who had to build their own water supply schemes. In 1904 the Irrigation Department came into being in the Cape and Transvaal Colonies. In 1912, after the Union of 1910, the Department of Irrigation of the Government of the Union of South Africa was established.

The great economic depression and the coincident drought during the late 1920s and early thirties gave impetus to the construction of several labour-intensive irrigation schemes such as the Vaal-Harts and Loskop State Water Schemes. After the Second World War, in the 1950s, South Africa started to change rapidly from a mainly agricultural and mining country to being more industrialised and urbanised. During that period the emphasis fell increasingly on urban and industrial water supplies which, however, did not preclude further irrigation development. From 1956 until the 1980s, a number of major State water schemes, such as the Orange River Project, the Tugela-Vaal, the Riviersonderend-Berg River and the Usutu-Vaal Water Transfer Schemes, were constructed.

The early 1970s saw the establishment of the (nominally) independent States of Transkei, Bophuthatswana, Venda and Ciskei (the TBVC States) and the self-governing territories (SGTs) of KwaZulu, KaNgwane, KwaNdebele, Lebowa, Gazankulu and QwaQwa, all of which had full jurisdiction over water resources within their boundaries. As they all shared catchments with others, permanent water commissions had to be established to manage common water resources.*

Continued on p 38

*All these states and territories reverted back to the Republic of South Africa with the promulgation of the new Constitution, on 27 April 1994.

THE VAAL RIVER SYSTEM

As an example of one of the country's major water systems, the Vaal River System, with its chronological development, is now illustrated. It is presented in terms of four distinct phases of its development, each of which is diagrammatically depicted and described below.

The Vaal River System before 1940 (Figure 3)

In 1922 the local authority, which has since become the Rand Water Board, and now *Rand Water*, built the Vaal Barrage near Vereeniging on the Vaal River to supply water to urban users in the Johannesburg area. The Vaal Dam, constructed about 60 km upstream by the Department of Irrigation, and completed in 1938, was the first major storage dam provided on the Vaal River. The yield of the dam, which was then about half its present-day capacity, was apportioned evenly between urban users and the Vaalharts Irrigation Scheme in the lower reach of the Vaal River.

A few other dams were also constructed in this period in the Vaal River catchment, mainly for irrigation purposes; the largest three being the Vaalharts Weir on the Vaal River, the Wentzel Dam on the Harts River and the Kalkfontein Dam on the Riet River. In the Crocodile River catchment to the north and the Olifants River catchment to the north-east, the Hartbeespoort and Loskop Dams, respectively, were also built to supply water for irrigation in those areas.

The Vaal River System between 1940 and 1960 (Figure 4)

During this period development concentrated mainly on the middle and lower reaches of the Vaal River. Additional dams for irrigation and urban use were built on some of the tributaries. Some of the more important developments were the building of the Rustfontein and Mockes Dams in the Modder River, to supply water to Bloemfontein, and the Erfenis and Allemanskraal Dams in the Vet and Sand Rivers, respectively, for irrigation water supply. Water was also supplied to the northern PWV area, and the link between the Vaal and the Crocodile catchments became one of the first of many interbasin transfer schemes in the country. The Vaal Dam was raised in the 1950s by the addition of 60 crest gates, and the Vaalharts Weir was also raised by the addition of "fish-belly" flap gates. The Orange Free State Goldfields water supply project was added, being supplied from the Balkfontein Weir on the Vaal River.

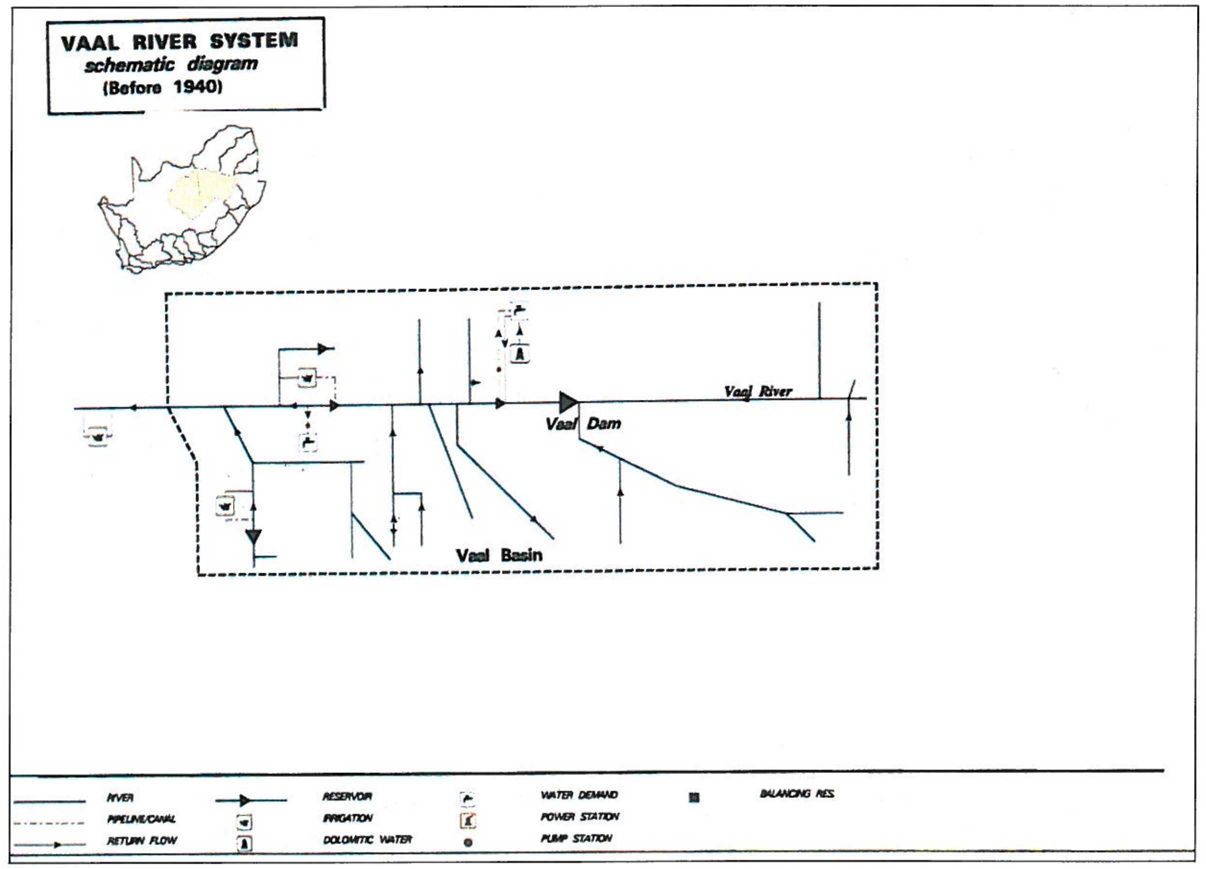


Figure 3

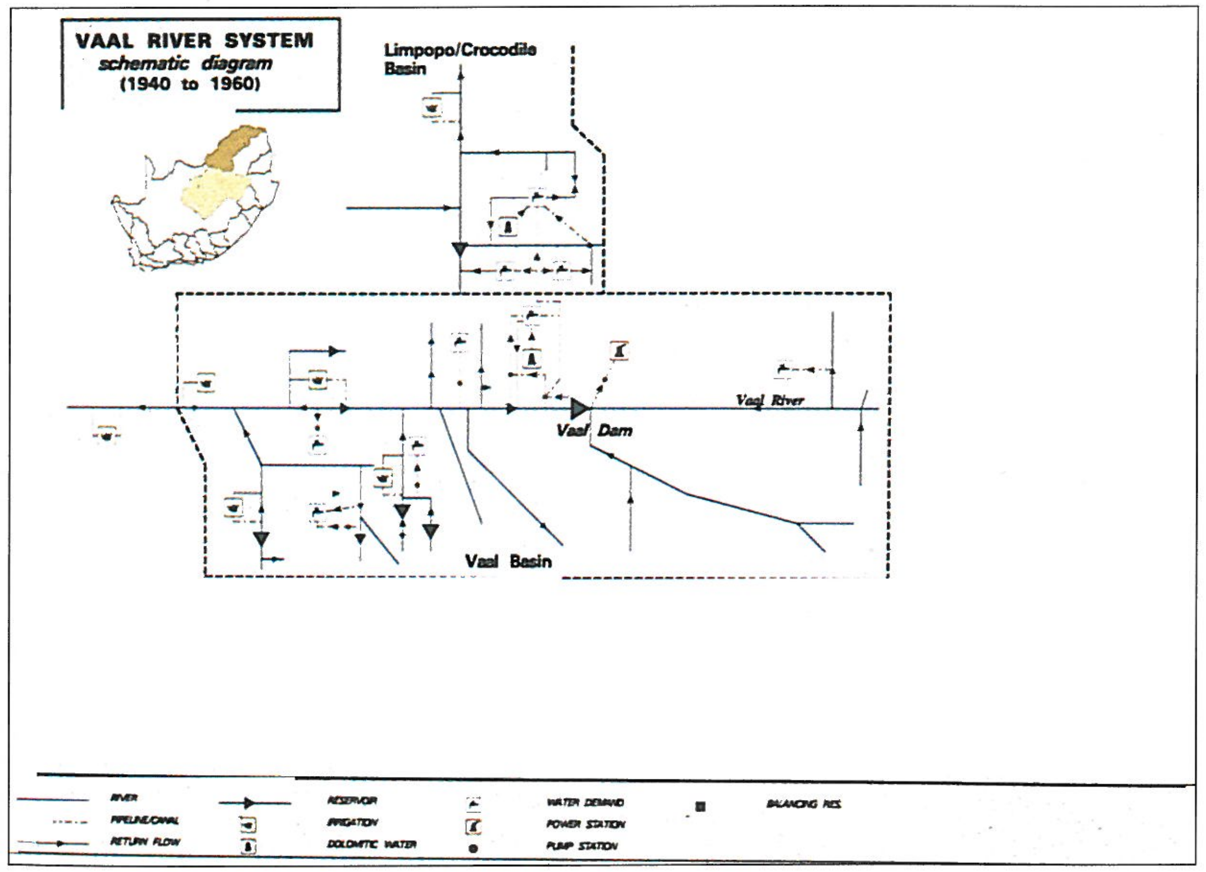


Figure 4

The Vaal River System between 1960 and 1980 (Figure 5)

The years between 1960 and 1980 saw the development of a number of interbasin transfer schemes mainly created to supply water for urban and industrial uses and for the cooling of thermal power-stations. Water from the Komati basin was supplied to coal-fired power-stations in the Olifants basin, while the Usutu River supplied water to power-stations in the Vaal and Olifants basins. Another important development was the building of a major scheme, the Tugela-Vaal Project. This water-transfer scheme included in its later stages the Drakensberg pumped-storage hydro-power project whereby water is stored in the Sterkfontein Dam and kept in reserve until required in the Vaal Dam. Power is produced for peak demand by means of the releases of water stored in the Driekloof reservoir (within the Sterkfontein reservoir) back to the lower lying Kilburn reservoir, through the Drakensberg hydro station in turbine mode. During off peak periods the normal pumping mode is resumed between Kilburn reservoir and Driekloof reservoir, the surplus passing over the dam wall into Sterkfontein reservoir. (See Figure 7). The net flow represents the actual transfer rate from the Tugela catchment to the Vaal catchment. A new intake for Rand Water's abstraction purpose was also added upstream of the Vaal Dam. The Bloemhof Dam was completed in this period to provide storage for users along the lower reaches of the Vaal, while the Douglas Weir was also rebuilt. The Grootdraai Dam, on the upper reaches of the Vaal River was also completed during this period.

The Vaal River System since 1980 and future planning (Figure 6)

Since 1980 the whole system has become far more integrated through additional linkages. The completion of the Grootdraai Dam upstream of the Vaal Dam and the supply of water to the ESKOM thermal power-stations in the Olifants basin effectively linked the Komati and Usutu basins to the Vaal River System. The Grootdraai Dam, again, was supplemented from dams in the Assegai River, a tributary of the Usutu River, and also from the Slang River, a tributary of the Tugela River. The capacity of the Tugela-Vaal Project was increased as well. An additional pipeline between the Usutu and Komati basins added another important link to the system.

During a very severe drought in the early 1980s, the flow of the Vaal River between the Vaal and Grootdraai Dams was reversed by the building of a sequence of seven temporary weirs whereby water was pumped upstream over each weir and on to the next. The possibility of rebuilding these weirs as permanent structures, when the supply to Grootdraai Dam will have to be supplemented in future, is considered feasible. In 1984 the Vaal Dam was again raised by the replacement of all 60 crest gates with higher gates, the rebuilding of the entire superstructure and outlet control house and the thickening of the main concrete wall of the dam as well as enlarging its three earth embankments, also adding a wave-deflector capping wall on top of the latter and providing flood absorption storage. The Vaalharts scheme was also upgraded and sophisticated flood-warning systems were installed in the Upper Vaal catchment.

Three additional Orange-Vaal water transfer links were built during this period, one upstream of the Hendrik Verwoerd Dam, to transfer additional water from the Caledon River to Bloemfontein, and two downstream of the PK le Roux Dam, to the Riet River and to Douglas, to support irrigation projects in the Lower Vaal River basin. The first phase of the Lesotho Highlands Water Project (LHWP) will deliver water from the Malibamatso River (Upper Orange, or Senqu, basin) in Lesotho to the Vaal River Basin early in 1997, and further phases are planned to follow as a joint undertaking by Lesotho and South Africa under the bi-national water treaty. As water demands continue to grow, it is envisaged that more water could be transferred from the Tugela River; and that the Mzimvubu River in the Eastern Cape Province, and possibly even the Zambesi River to the north, could be considered to be linked to the Vaal River System during the next century.

Continued from p 36

During that period the Department again changed its character from that of a bulk water supplier to a water resource manager. While still being responsible for the development and operation of the national water infrastructure, more emphasis was put on the formation of water boards and irrigation boards, and in some areas regional service councils took over the supply of water for domestic and industrial purposes. Many metropolitan areas and towns had their own water supply structures and controlling bodies were set up to augment these services or to provide them in areas without

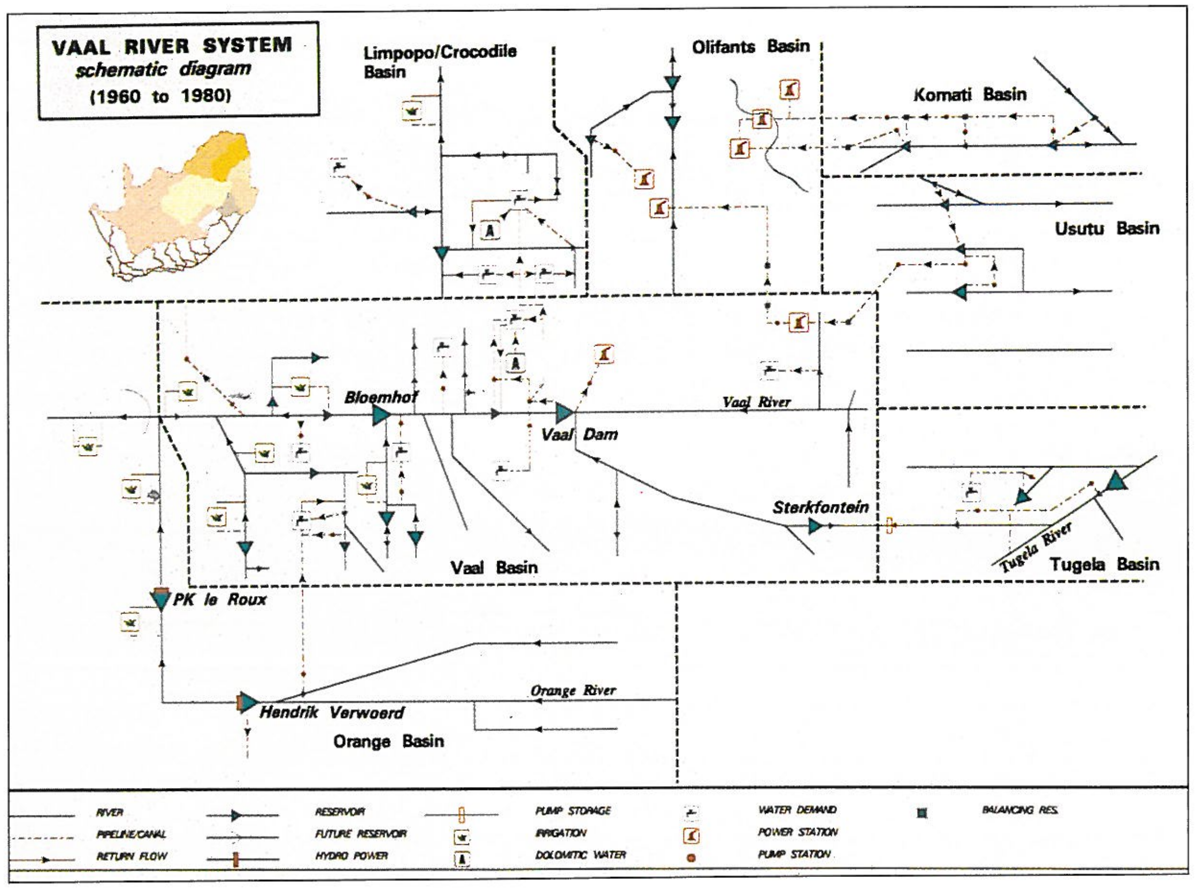


Figure 5

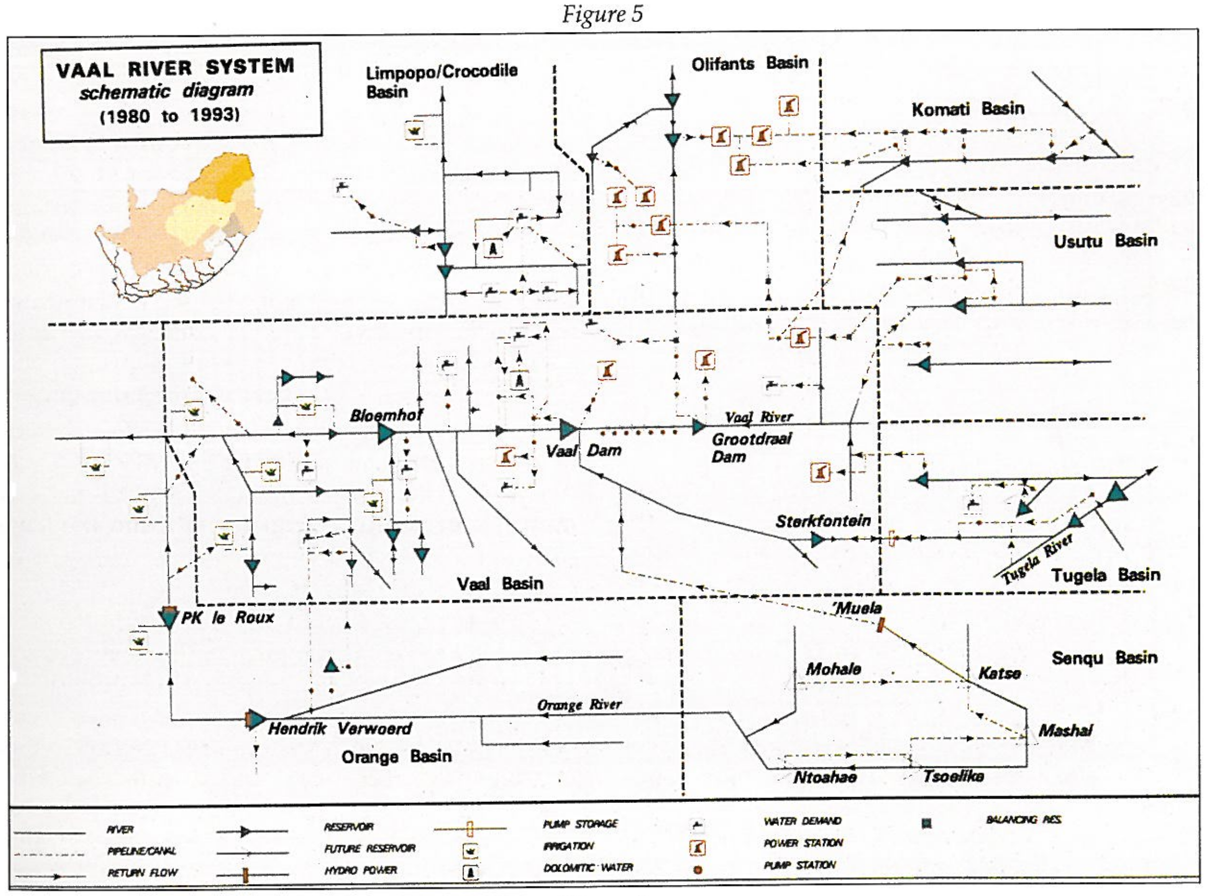


Figure 6

suitable authorities. Because of constraints these initiatives were limited to the remaining area of the Republic of South Africa, and the TBVC States and SGTs were expected to do the same within their own areas of jurisdiction.

More recently, because of the international nature of certain schemes and also to gain access to capital markets, development of infrastructure was initiated by the Department of Foreign Affairs which was instrumental in the formation of authorities such as the Trans-Caledon Tunnel Authority (TCTA), the Lesotho Highlands Development Authority (LHDA) and the Komati Basin Water Authority (KOBWA).

FUTURE OUTLOOK

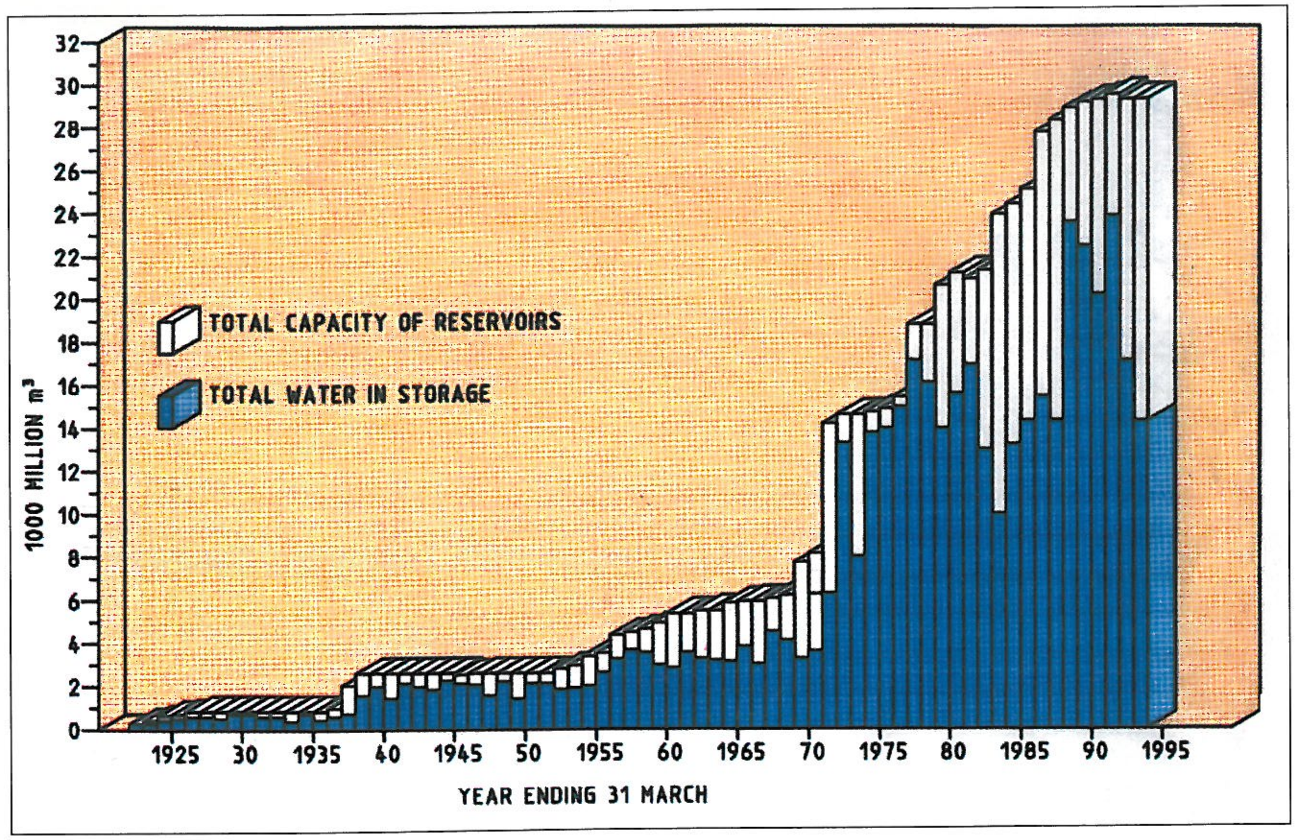
Water is seen as a national asset on which the economic and social development of South Africa depend. Water is also a public asset and not subject to the normal free market mechanisms of demand and supply, which determine the price and allocation of goods. Government participation is therefore a necessity and, because of the increasing scarcity of the resource, its strategic importance and the geographical mismatch of demand and supply, the overall control has to be exercised by the central government. The State nevertheless intends to continue with its long-standing policy of devolving control and responsibilities to lower levels wherever possible.

To cope with the increasing pressures from a growing population and burgeoning economy, future water management will have to be characterised by increased sophistication in both the utilisation as well as the application of this scarce resource. While in future there will be water supply systems constructed that, in scale and complexity, will eclipse those of today, equal attention will be required for the conservation of the resource to ensure its availability to sustain the country and its people in the long run.

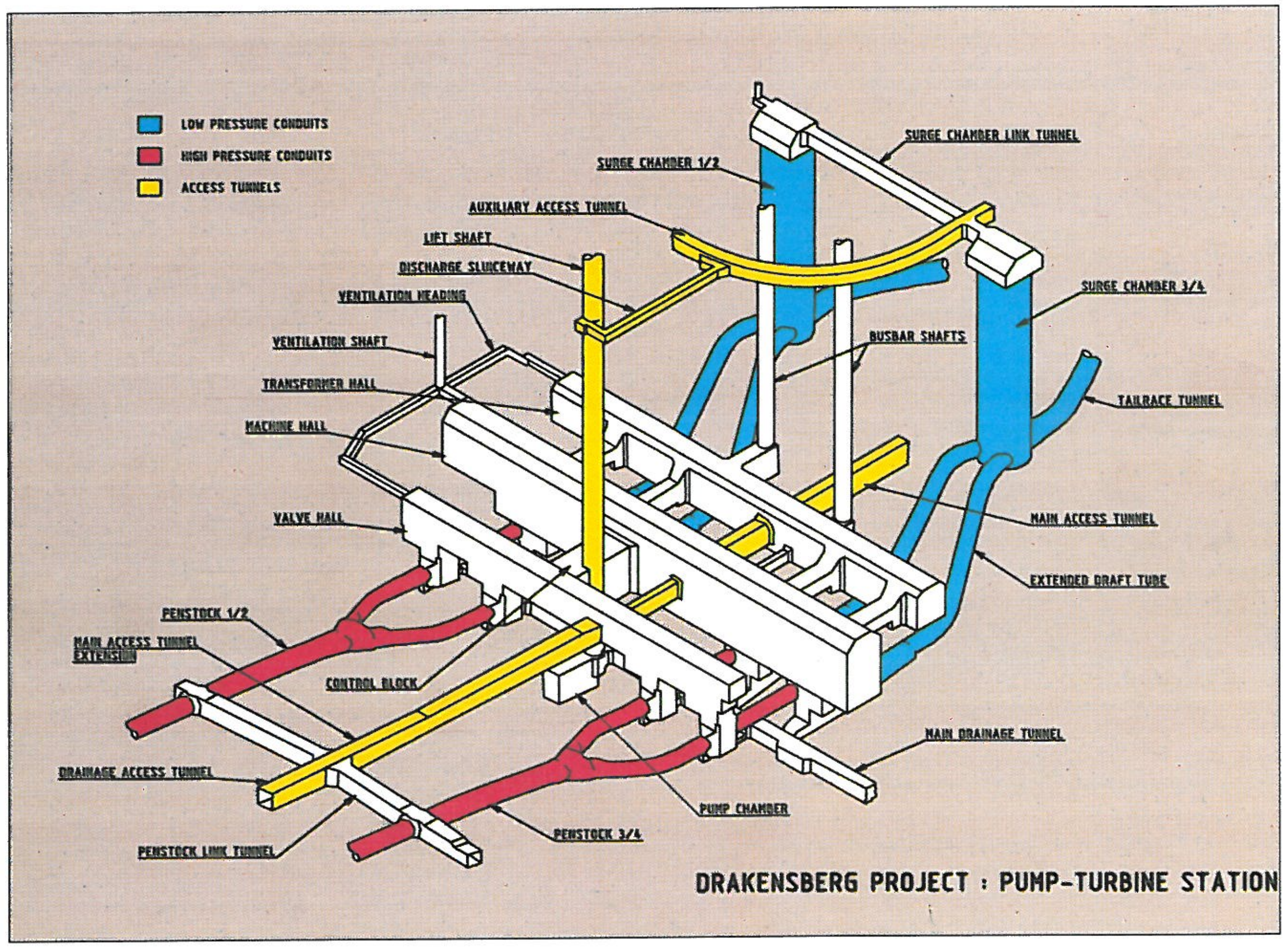
REFERENCES

Bodill TS. *History of the Port Elizabeth Water Supply.* Internal Report: City Engineer's Department, Port Elizabeth

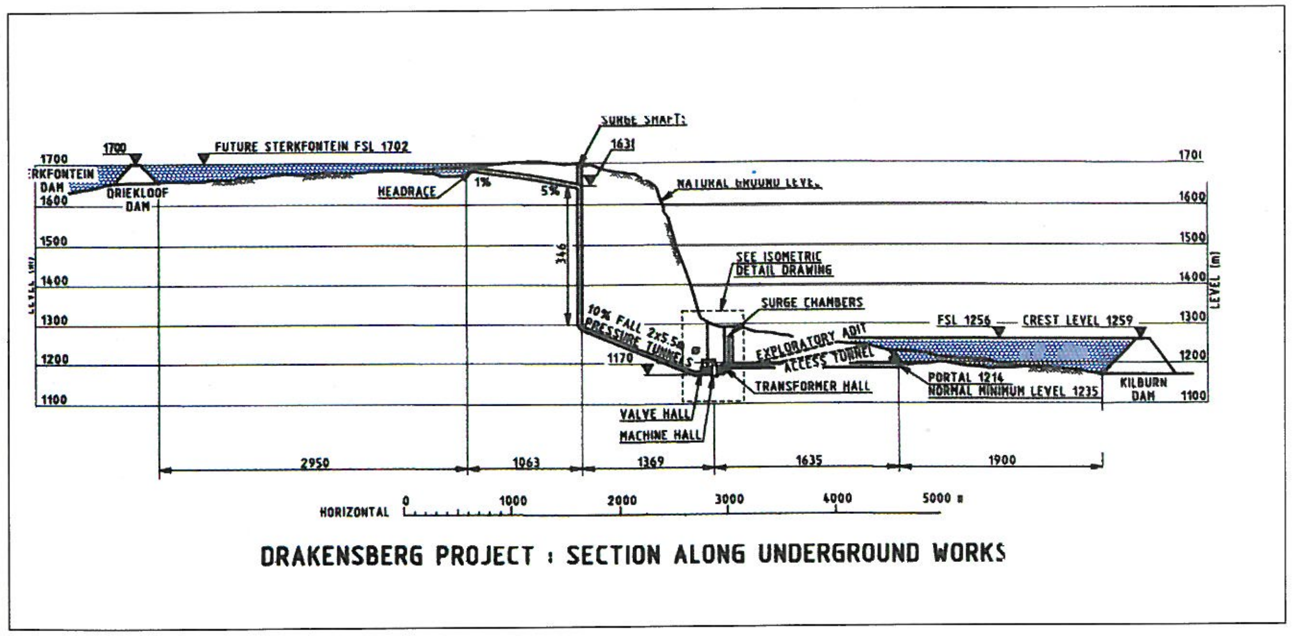
South Africa, Department of Water Affairs (1986). *Management of the water resources of the Republic of South Africa,* Pretoria



Total capacity of reservoirs and water in storage since 1920 (DWA)



DWAF Draughting Services Courtesy Eskom



Courtesy Eskom

Figure 7: Beneficial utilization of a water transfer and supply project's features also for peak power generation. The Tugela-Vaal Scheme's Drakensberg Pumped Storage Project.

Table 1. Main Water Supply Systems in Southern Africa

Name	Source Rivers	Recipient Rivers	Principal Dams	Tunnels	Canals	Pipelines
Algoa System	Kouga Krom Orange Swartkops		Paul Sauer Loerie Churchill Charlie Malan Hendrik-Verwoerd Groendal	Orange-Fish Fish-Sundays	Gamtoos Sundays River	Pipelines to Port Elizabeth from Loerie, Churchill, Charlie Malan and Scheepersvlakte Dams
Amatole System	Kubusi	Nahoon Buffalo	Wriggleswade Nahoon Laing Bridle Drift	Wriggleswade Kei Road Northslope (proposed)	Wriggleswade	Various pipelines
Bloemfontein Water Supply	Modder Caledon		Mockes Mazelspoort Rustfontein Welbedacht Knellpoort		Knellpoort	Extensive pipeline distribution system Caledon-Bloemfontein
Lesotho Highlands Water Project - Phase 1	Senqu (Orange)	Vaal	Katse (1A) Mohale (1B)	Katse-Muela (Transfer) Muela-Axle River (Delivery) Mohale-Katse		
Mossel Bay Regional Water Supply System	Moordkuil Great Brak		Klipheuwel Wolwedans			Extensive pipeline distribution system
Mgeni System	Mgeni		Albert Falls Midmar Inanda Nagle	Midmar-Pietermaritzburg Inanda-Wiggens Nagle-Durban Heights		To Pietermaritzburg To Durban
Orange River Project	Orange	Little Fish Great Fish Sundays Riet Vaal	Hendrik Verwoerd PK le Roux	Orange-Fish Cookhouse Fish-Ecca	Fish-Sundays Lower Sundays GWS Lower Fish GWS Van der Kloof Sarel Hayward Orange-Douglas	
Western Cape System	Groot Berg Palmiet Various	Rivier Sonderend and Berg (reversible)	Steenbras Wemmershoek Kogelberg-Rockview Voëlvlei Theewaterskloof	Franschhoek Jonkershoek Stellenbosch-berg	24 Rivers	Voëlvlei Wemmershoek Steenbras Stellenbosch-berg

Table 1 continued right

Table 1 continued from left

Vaal River System (subsystems)	Source Rivers	Recipient Rivers	Principal Dams	Tunnels	Canals	Pipelines
1. Komati-Olifants	Komati	Olifants	Vygeboom Nooitgedacht			Komati-Olifants
2. Usutu-Komati	Usutu	Olifants	Westoe Jericho Morgenstond	Westoe-Jericho		Usutu-Olifants
3. Usutu-Komati	Usutu	Komati	Westoe Jericho Morgenstond Nooitgedacht			Camden-Nooitgedacht
4. Assegai-Vaal	Assegai	Vaal	Heyshope Grootdraai		Heyshope	Geelhoutboom Vaal
5. Slang-Vaal	Slang	Vaal	Zaaihoek Grootdraai			Zaaihoek Vaal
6. Vaal-Olifants	Vaal	Olifants	Grootdraai		Grootdraai-Grootfontein	Grootfontein Olifants
7. Tugela-Vaal	Tugela	Vaal	Woodstock Driel Sterkfontein	Drakensberg	Driel-Jagersrust	
8. Vaal-Harts	Vaal	Harts	Vaal Bloemhof		Vaal Harts	

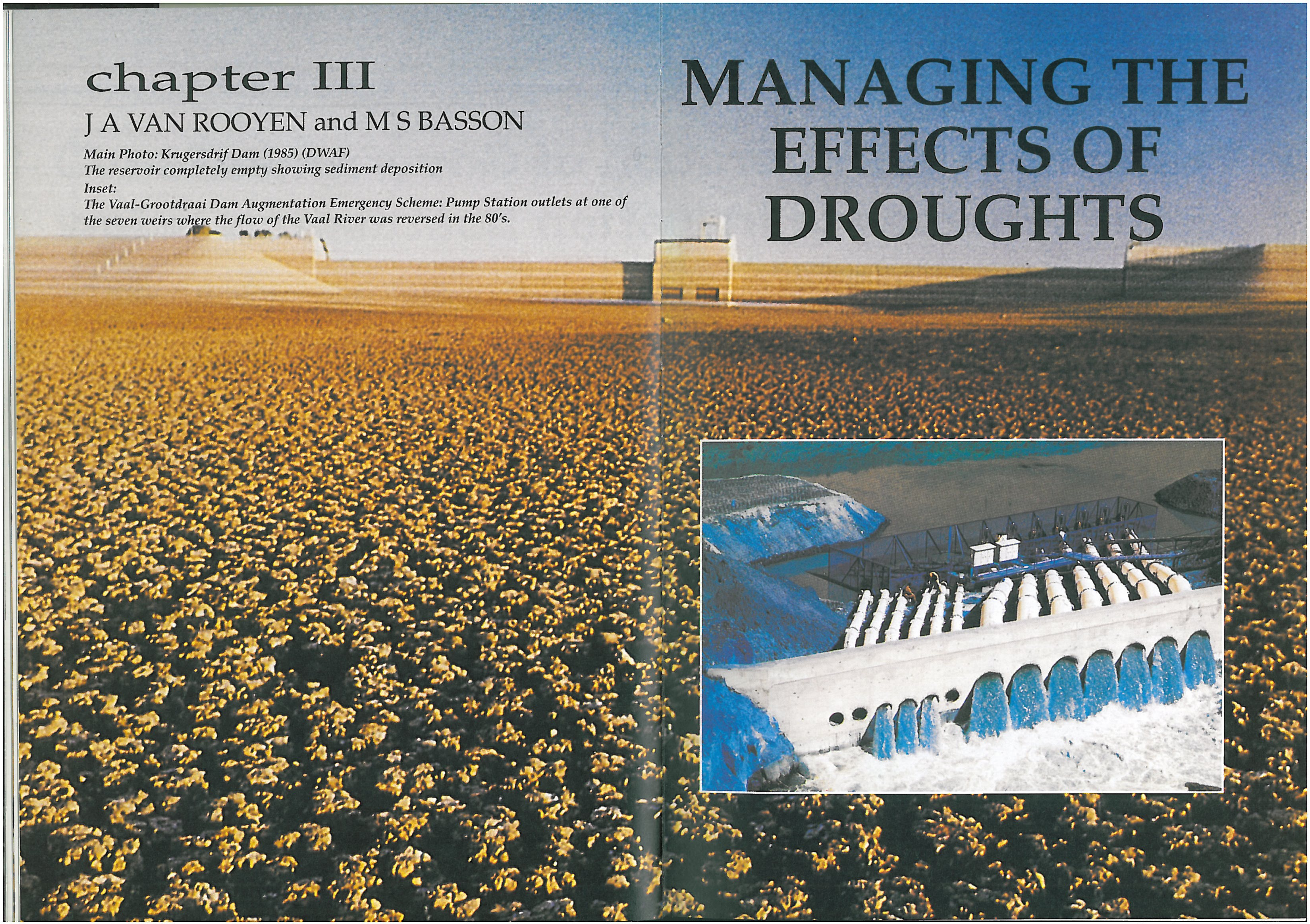
Table 2. Water Boards

Name	Area	Rivers	Dams <u>(Department of Water Affairs)</u>
Bloem Water	Bloemfontein	Caledon Modder Modder	<u>Welbedacht, Knellpoort</u> Mockes <u>Rustfontein</u> Mazelspoort
City of Cape Town including Eskom	Cape Town and Western Cape	Berg Palmiet Rivier Sonderend	Wemmershoek Steenbras <u>Kogelberg, Rockview</u> <u>Misverstand</u>
City of Port Elizabeth	Port Elizabeth	Van Stadens Krom Kouga Orange	Van Stadens Churchill, <u>Charlie Malan</u> <u>Paul Sauer</u> <u>Hendrik Verwoerd</u>
Magalies Water	North-PWV-Bronkhorstspruit Rustenburg Thabazimbi Bronkhorstspruit	Crocodile-West Elands Pienaars Bronkhorstspruit	<u>Vaalkop</u> <u>Roodekopjes</u> <u>Roodeplaat</u> <u>Bronkhorstspruit</u>
Mgeni Water	Pietermaritzburg Durban	Mgeni	<u>Midmar</u> <u>Albert Falls</u> Henley, Nagle, <u>Inanda</u>
Mhlatuze Water	Richards Bay	Mhlatuze	<u>Goedertrouw</u>
Northern Transvaal Water Board	Pietersburg Louis Trichardt	Letaba Luvuvhu	<u>Ebenezer</u> <u>Albasini</u>
Phalaborwa Water Board	Phalaborwa	Olifants	Olifants Barrage <u>Blyde</u>
Rand Water	Pretoria Witwatersrand Vereeniging (PWV) area	Vaal	Vaal Barrage <u>Vaal Dam</u>

chapter III

MANAGING THE EFFECTS OF DROUGHTS

J A VAN ROOYEN and M S BASSON

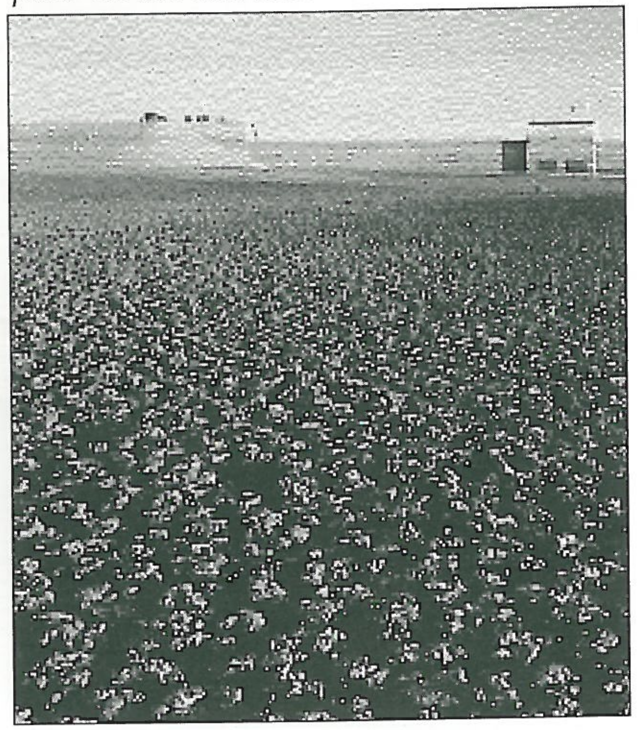


Main Photo: Krugersdrif Dam (1985) (DWAF)
The reservoir completely empty showing sediment deposition
Inset:
The Vaal-Grootdraai Dam Augmentation Emergency Scheme: Pump Station outlets at one of the seven weirs where the flow of the Vaal River was reversed in the 80's.

MANAGING THE EFFECTS OF DROUGHTS

by J A van Rooyen and M S Basson

The term drought*, which generally refers to a shortage of water, has different meanings to different people, depending on how they may be affected by a drought. The farmer is likely to experience it as a lack of sufficient rainfall, the water supply authority as insufficient resources to meet its demands, while the city dweller is likely to learn about it in the media and experience it in the form of restricted water supplies. As this book deals with dams and river systems, the droughts considered here refer to prolonged periods of exceptionally low river flow. This chapter focuses on ways to deal with such droughts in order to ensure that a reliable but still affordable supply of water can be maintained.*



Krugersdrift Dam: Evidence of severe drought

Droughts are an inherent feature of nature and even in wet areas, river flows vary from year to year. These variations are, however, much more pronounced in the dryer regions of the world and are especially characteristic of South African rivers. A typical example is given in Figure 1, which illustrates the extreme variation in annual river flow at the Vaal Dam, the central dam in the most important water resource system in the country. The annual runoff at the Vaal Dam can vary from as much as 300% to as little as 10% of the mean annual runoff.

To utilise this highly variable runoff efficiently, storage is required for the carrying-over of water from the times when surplus runoff occurs to times of shortage or droughts. As periods of below average flow of 5 to 10 years' duration often occur in South Africa, large impoundments are required to bridge these periods. Dams in South Africa are thus constructed to create storage reservoirs that are exceptionally large in terms of the average annual flow, compared to the more humid parts of the world (South Africa, Department of Water Affairs, 1986). Reservoirs which can store two to three times the mean annual flow of the river on which they are built, are therefore not uncommon. In order to utilise the carrying-over capabilities of a reservoir to the full, the water level must inherently fluctuate between full supply and lower levels. Only during extreme drought conditions, however, should it approach the lowest drawdown level as reserves are withdrawn to maintain supplies.

Storage of large volumes of water for the very long carrying-over periods that may be necessary during severe drought sequences, can result in excessive evaporation from surface areas. This is especially true for reservoirs with unfavourable storage basins. On most rivers only a precious few dam sites with favourable reservoir characteristics occur, while there is also only limited financial means for the construction of dams.

The result is that it is not feasible to supply enough storage to cater for the full supply of all demands under severe drought conditions. Additional measures must be devised to bridge the drought periods, such as the suppression of demand by the introduction of water restrictions; also considered to be a form of *demand management*.

Although the occurrence of droughts is typically regional and sub-continental in nature, it is a well known phenomenon that the severity of droughts generally varies from one river basin to another for a specific drought period. The development of the interbasin transfer schemes and systems as described in the previous chapter, is therefore not only meant for the direct augmentation of resources which are excessively utilised, but also offers the opportunity for one river basin to support others during times of drought.

Managing droughts is a complex problem comprising different elements, and is described in more detail under the headings to follow.

SYSTEMS APPROACH

Due to the fact that water demand exceeds the supply capability of local resources in many parts of the country, a number of interbasin transfer schemes were developed. This gave rise to the evolvement of complex water resources systems comprising reservoirs, weirs, tunnels, pumping stations, canals and pipelines — all of these stretching over several river basins. The Vaal River System, as shown on the simplified map in Figure 2

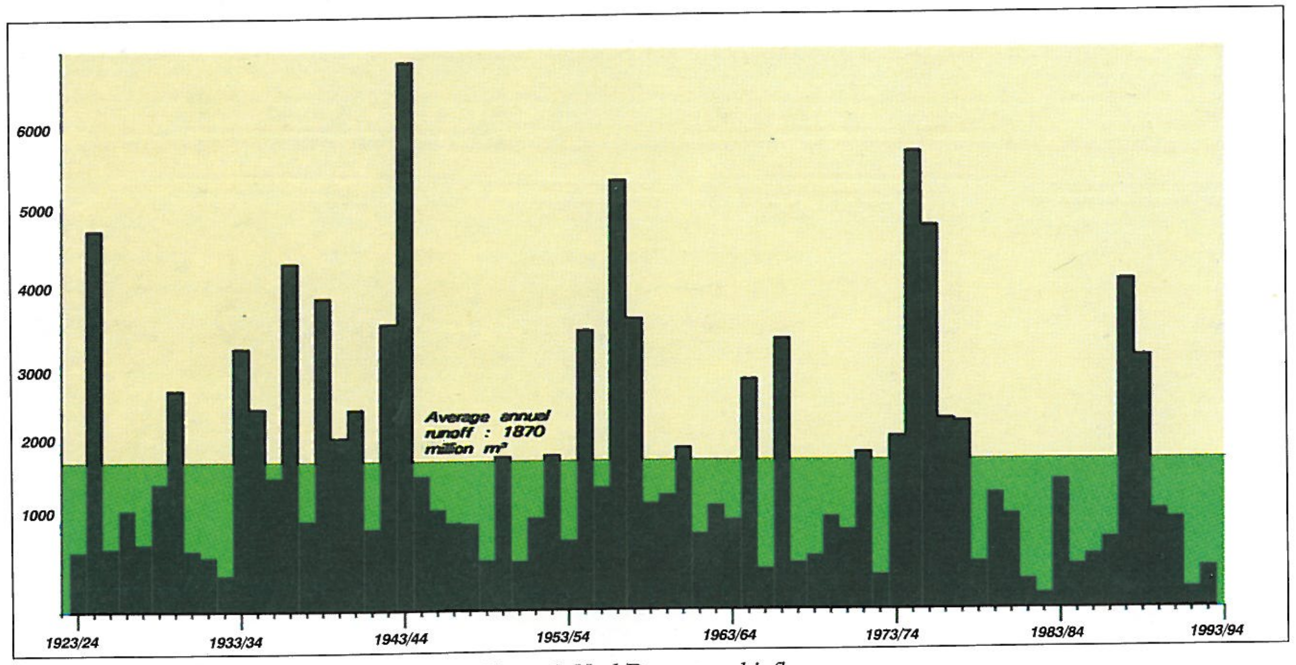


Figure 1: Vaal Dam annual inflows

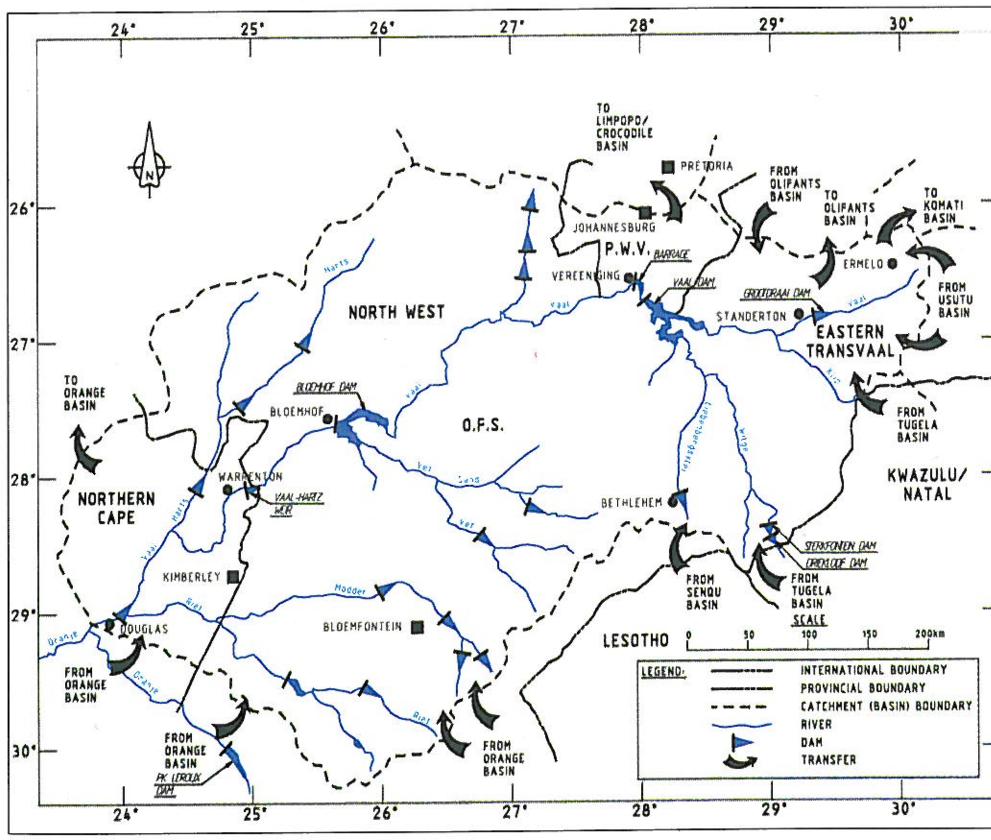


Figure 2: Map of the Vaal River System showing water transfer points (see key map, Figure 9)

serves as a good example in this respect. (Refer Chapter II on its development).

The most efficient utilisation of the combined resources of a complex water resource system such as the above, is not achieved by operating each component continually at its own optimal level of yield. All components should rather be simultaneously considered as one unit, in a so-called systems context. In doing so, it is often advantageous to place higher demands on those components in the system that have temporary excess capability, in order to support other components which may temporarily be under short supply because of a drought. In this way a total yield for the whole system can be achieved that is larger than the sum of the yields of the individual components. The continued dynamic interaction amongst all components of the system is thus necessary. To ensure unrestricted flexibility in this respect, the capacity of the interbasin water carriers needs to be sized for the transport of the appropriate quantities of water. As this may have significant cost implications, the cost of providing the full conveyance requirements must be carefully weighed against the increase in the assurance of supply that can be attained.

In order to determine the inter-component support requirements and capabilities, system analyses are being applied to evaluate all the large water resource systems in South Africa. This includes the Vaal River System which supplies the urban, industrial and mining areas forming the economic heartland of the country, as well as other systems supplying the Cape Town, Port Elizabeth, East London, Bloemfontein, Durban and Richards Bay metropolitan regions. Most of the large irrigation projects in the country are also covered in this way.

During the course of these analyses, certain new approaches and techniques were developed to give a better understanding of the risks involved in the operation of complex systems and to enable better use of the very variable water resources of the country.

The two key developments which contributed to the enhanced understanding of the characteristics and behaviour of water resource systems and enabling the *probabilistic management* thereof, are:

- the formal recognition and use of different classifications of water yield, together with
- the extensive application of multi-site synthetic (stochastic) generation of streamflow.

In the classification of yield, distinction is drawn between *base yield*, which is the water that can reliably be drawn from a system; *non-firm yield* which is what can be supplied most of the time, but cannot be relied upon; and *secondary yield* which represents additional water that can be withdrawn from a system during times of excess. Base yield therefore represents the firm component of yield to be supplied at a specified assurance, while non-firm yield is largely indicative of inter-component support requirements, and secondary yield serves as a measure of *inter-component support* capability as well as further development potential. The base yield plus non-firm yield is what can on average be drawn from a system and is a function of the targeted abstraction rate, while the summation of the base yield, non-firm yield and secondary yield represents the *total capability* of a system. The synthetic generation of streamflow is further discussed in the next paragraph.

This methodology has proved to be of exceptional benefit as a *management tool* under varied conditions and applications, with resultant large financial benefits. (Van Niekerk and Basson, 1993). More comprehensive descriptions of the technology are given in papers by Basson, Triebel and Van Rooyen (1988), McKenzie and Allen (1990) and Van Rooyen and Basson (1992).

OCCURRENCE AND LIKELIHOOD OF DROUGHTS

The periods of observed streamflow records in South Africa typically vary between 20 and 70 years which is only a very brief glimpse in terms of the long period of time of recorded history. If it is considered that drought periods of as long as 10 years commonly do occur, the streamflow records can at best only contain a bare minimum of severe drought cycles. They also provide but a limited perspective of possible future events, and it is most likely, therefore, that more extreme events could be experienced in future than have been observed in the past.

To overcome this limitation, extensive use is made in the system analysis of the synthetic generation of streamflow sequences. Use is made of stochastic models which can create streamflow sequences with the same statistical characteristics as that of the observed streamflow sequence, but can also produce unlimited combinations of annual (or monthly) flows containing higher and lower extremes than those observed. This is illustrated by the examples in Figure 3.

The model also accounts for the *serial correlation*, that is any relationship which may exist between the streamflow in one year and that of the following year. Of even greater importance in the management of a water resource system which extends over a large geographic area, is the proper preservation of relationships amongst streamflows at various key locations. This *cross-correlation* amongst streamflow sequences is one of the key factors to determine the

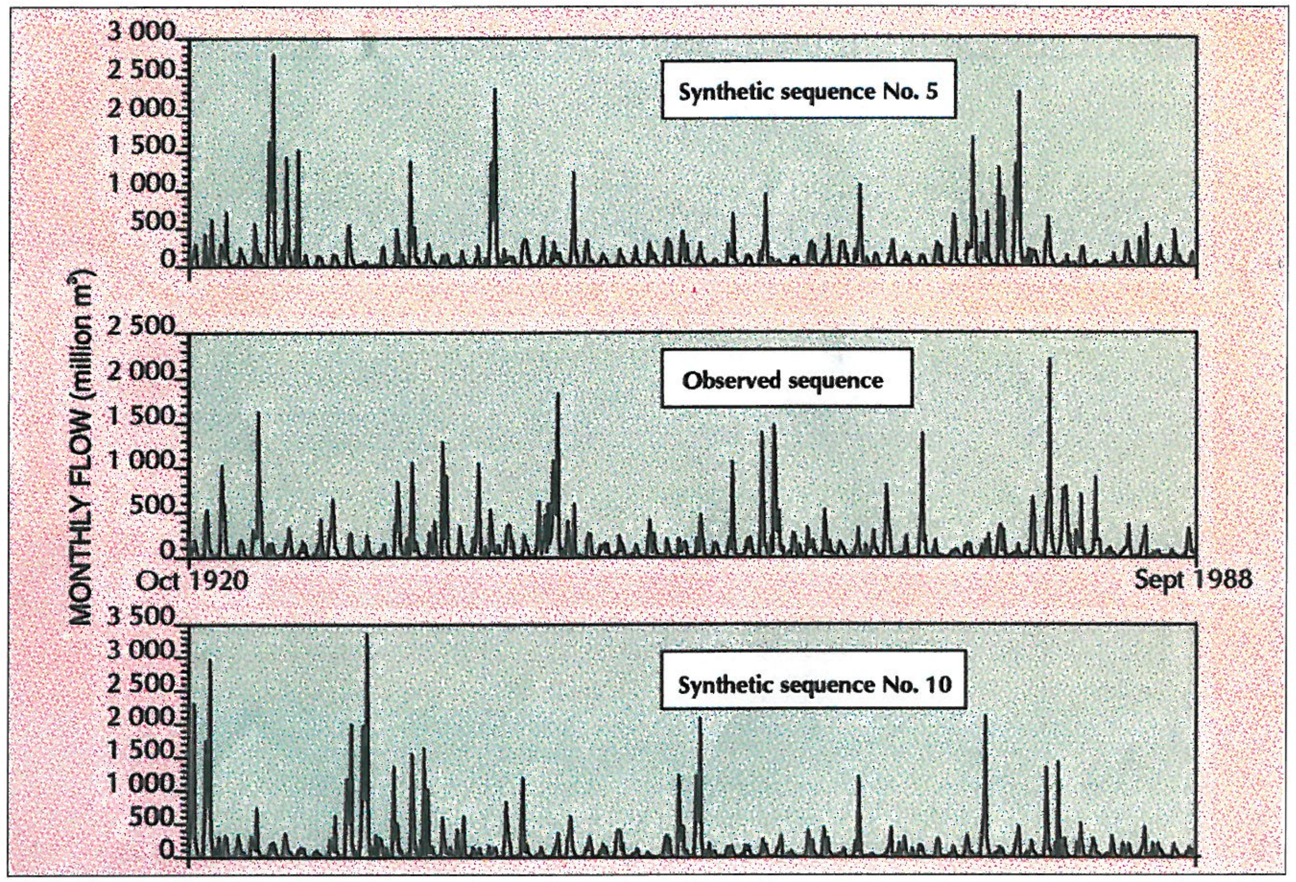


Figure 3: Comparative plots of observed and synthetic records

advantages that can be gained by inter-component support during times of drought.

The preservation of cross-correlations is ensured through the simultaneous multi-site generation of the *synthetic sequences*. Strong relationships exist between streamflow and climatic conditions; between climatic conditions and reservoir evaporation as well as irrigation requirements, and others, and are also accounted for in the models.

Owing to the high variability of streamflow in semi-arid regions such as South Africa, significant development work was required to produce a *stochastic model* capable of generating synthetic streamflow sequences that reliably represent the observed streamflow (Pegram and McKenzie, 1991). Comprehensive verification procedures are also required to ensure the proper calibration of the model with respect to each individual flow record as well as the correlation amongst multiple sites. Figures 4 and 5 are examples of typical verification tests. In both cases it is expected that the observed base records should fall well within the spread of the stochastic results.

One of the greatest advantages of using synthetic flow sequences (stochastic hydrology) is that hundreds of streamflow sequences of the same duration as the base record can be generated and analysed, compared to the one observed record only. The significantly greater stability of yield analyses based on stochastic hydrology is further demonstrated by the fact that a critical low flow period, which would, over a very long period of time, occur once in 100 years on average, has only a 63% probability of occurring in any specific period of 100 years duration — and consequently a 37% probability of not occurring. Should an observed record of only 50 years be available, the probability of capturing a 1:100 year low flow period therein would only be 39%.

Curtailments in water supply

A very effective method of managing the effects of severe droughts is to introduce water restrictions during the times of short supply. The questions that should then be addressed are at what stage, and to what degree the restrictions have to be implemented. As all water users do not have the same tolerance to water restrictions, the very unpopular decision on which user groups restrictions should be applied to, must also be made.

The water resource systems in South Africa supply water to a wide spectrum of users. They all have different requirements regarding the reliability of their supply. The different user categories that are normally supplied from large systems are the

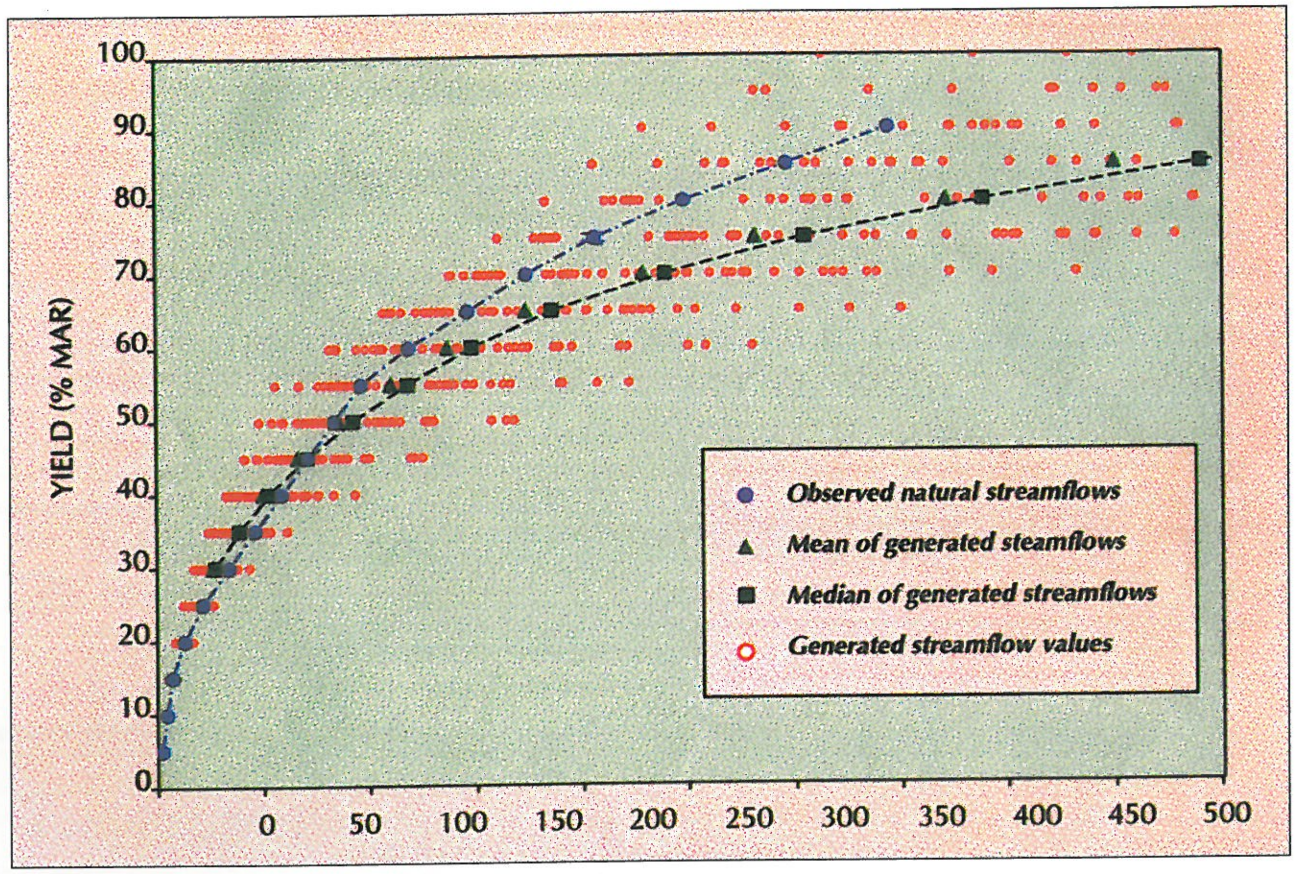


Figure 4: Example of yield vs storage capacity test

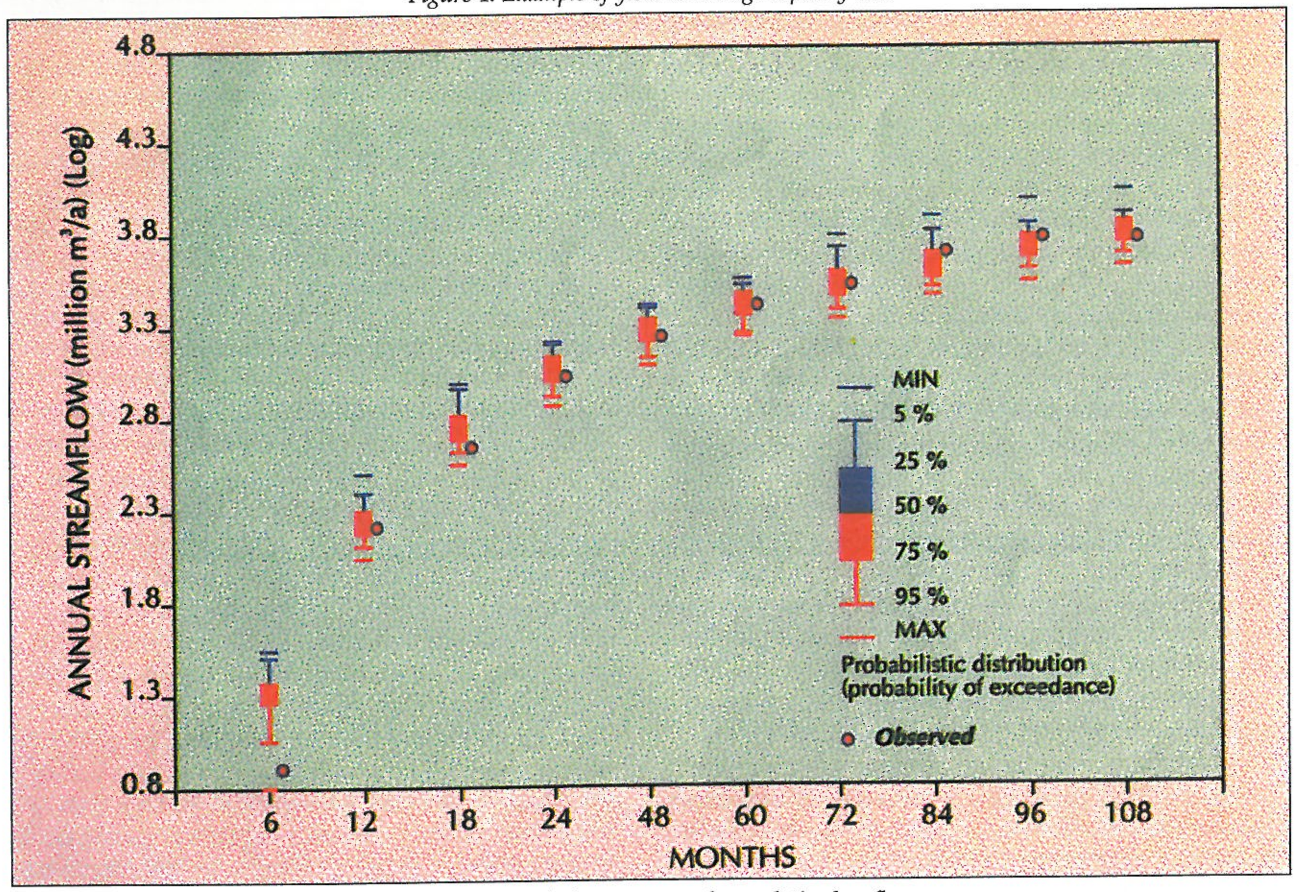


Figure 5: Statistical occurrence of cumulative low flow

urban users, who are again divided into domestic and industrial users; agricultural, of which irrigation is the biggest user; mining; cooling in thermal power stations, and also other industries that may be regarded as strategic users. Another very important user is the environment. In some systems the environmental demand can be met by releasing water for other users further downstream, but often specific releases may be necessary for the environment.

In the Vaal River System, for example, the users and their requirements were categorised into three priority classes, as described in the following paragraphs :

• The first major water user category is the urban sector, whose needs can be divided into use for domestic and for industrial purposes. Domestic use is further subdivided into three priority classes, with garden irrigation in the *low* priority class, luxury or convenience use inside the house as *medium* priority and the use for sanitary and other basic human needs as *high* priority. It must be realised that, in high density living areas as well as the central business districts, the quantity that is normally used for garden irrigation is very small and for all practical purposes probably non-existent. In the poorest neighbourhoods the total water use falls into the category of basic human needs and is therefore all classified as high priority use. Industrial use in the urban areas is divided into a small portion that may be regarded as medium priority and the bulk as high priority. As water restrictions were not uncommon during the past twenty years, the industries in the Vaal River System supply area in general have adopted very efficient water use methods. The restriction of water for industrial use can very quickly lead to great economic loss to the country — which is unacceptable.

• The big coal-fired power-stations, which use water mainly for cooling purposes, together with the petrochemical industries, are situated on the coal fields outside the main urban centres. These users of water have also adopted very efficient water-use technologies that leave little room for wastage. Therefore, even a very small restriction on their water consumption will have serious consequences. The power-stations, if rationed on their water use, will immediately have to curb power generation — which not only implies considerable direct losses from power sales, but will also have a serious ripple effect throughout the economy. These water users are collectively called *strategic users* and their total demand is regarded as high priority use.

• The Vaal River System supports extensive irrigation areas over the total catchment area. The largest single irrigation area in the country, the Vaalharts Scheme of 36 000 ha, is one of these. The irrigation water use in this area is divided into 50% low priority, 30% medium priority and the last 20% high priority, which may be regarded as necessary for the survival of perennial crops.

It must, however, be realised that there is a fair amount of subjectivity and uncertainty around the exact split in user priorities, and much research is still required to refine this approach. Between 1983 and 1987 a severe drought in the catchment areas of the Vaal River System resulted in the introduction of water restrictions. The prioritisation, as described, was partly deduced from the experience gained during that period. A study was done to determine the effect of water restrictions on the industrial use of water in the Vaal River System. The high value determined for water used in industry confirmed the high priority allocated to this category of water use (South Africa, Department of Water Affairs, 1991).

It may be argued that the *high priority class* may be divided even further because it is inconceivable that water will be supplied to industry when people are short of water for basic human needs. In the planning of water resource development, the high priority class is given a very high assurance of supply and is actually protected by the water restrictions for the other classes. It is therefore not really anticipated that users in this class will ever be restricted. In the unlikely event that this may actually happen, the use in that class will undoubtedly be further prioritised.

The principles of introducing water restrictions are to incrementally impose curtailments, as storage levels in reservoirs drop below what is required to sustain full supply. This is achieved by taking into account the supply capability of the system at the time of the decision, and the introduction of curtailments firstly on the lower priority users, to protect the higher priority classes of water use. This approach ensures the lowest economic damage and least social disruption.

To facilitate the above, certain probabilistic techniques have been developed to assess the supply capability of a system (or subcomponent) at the prevailing state of storage at the relevant time during the season (South Africa, Department of Water Affairs, 1986). Basic to the approach is the development of draft-yield characteristic curves that represent the *probabilistic yield capability* of a system over a selected operational time horizon, starting at the prevailing state of storage.

REAL-TIME OPERATION

To ensure that a water system is utilised optimally and the users are supplied in accordance with their assurance of supply requirements, it is necessary, at regular intervals, to take formal decisions on the sufficiency of resources and the allocation of water. Decisions are taken in preparation of the coming period and are based on the prevailing state of storage as well as the latest demand projections.

Decisions regarding the Vaal River System are taken annually at the beginning of May. The primary reason for the May decision date is because it falls at the end of the rainy season, which means that the system will be fairly stable for the following six dry months and sudden changes in storage are highly unlikely. Another reason is that May falls prior to the irrigation farmers' main planting period for cash crops. The farmers can only make meaningful decisions on their cropping schedule if they know about the availability of water beforehand. They will suffer substantial financial losses if a full crop is planted and they are then placed under water restrictions sometime during the growing season.

Practical problems in enforcing water restrictions in large urban areas also require that decisions must not be changed too frequently. The steps in which restrictions are increased should be sufficiently large to help the local authorities in implementing a meaningful restriction policy.

It can be very effective to make more than one decision date during the year if the user can quickly respond to the decision. In the operation of some of the subsystems of the Vaal River System, which supplies water to the majority of the country's power stations, three decision dates, regularly spaced throughout the rainy season, are being used. This allows for a quick response to changes in the system and a resultant improvement in the assurance of supply to this very important user.

The decision on the supply of water taken on each decision date should not only consider the supply situation for the approaching season, but must also ensure that the water supply situation for future years are within acceptable assurance limits. Consideration is always given to the supply capability over a period of several years — the specific period varying from case to case, depending on the carrying-over capabilities of the system in question, as well as the typical duration of severe droughts. In the Vaal River System, as well as in some of the other important systems supplying large metropolitan areas, the assurance of supply over the next five years is always considered. The decision is revised at least annually, and more frequently in some of the less regulated systems. This means that at each decision date the supply situation for the next five years is considered and the necessary decisions are taken to safeguard the high priority users. Reconsidering the decision at least once a year means that the operation of the system is continually adapted for ever changing conditions, to ensure that potentially catastrophic situations do not develop.

On the annual decision date, the supply capabilities for the next five-year period of each component in the system are determined, based on the prevailing storage in that component. The supply capability of each subsystem is first compared to the direct demand from that subsystem. In doing this, the various assurance requirements of the different water users are accounted for.

The potential support capabilities of the various components of the system with respect to one another are then considered and the supply through the total system is balanced as far as the support capabilities of the subsystems will allow.

If it is found that shortages still exist after the demand and the balanced supply are matched, water restrictions are introduced to lower the usage and to ensure protection of supply to the higher priority users. The exact level at which the water restrictions will be introduced is determined in an iterative process, where the usage is incrementally restricted until a balance between the restricted demand and the supply capabilities is attained.

The system is then operated at this restricted demand level until the next decision date when the situation is again assessed to determine whether it is necessary to change the restrictions. If at any time during the rainy season the inflow increases markedly and there is reason to believe that the restrictions can be slackened or even totally lifted, the analysis is immediately updated with the latest information and the decision revised.

Although this chapter deals with *drought* management, it must be pointed out that the same methods can be used during times of *surplus* supply capability, to attain other objectives. If the reservoirs in the main stream of the Vaal River System, for instance, are fairly full at the decision date and the demand is less than the yield of the system, a decrease in the importation of water from some of the interbasin transfer schemes can be considered. These importation schemes deliver water at very high pumping heads, and considerable savings in energy and pumping costs can be achieved. Another way of utilising a temporary surplus capacity is to release water to alleviate water quality problems that may exist in certain river reaches.

Once steps on the allocation of water from the respective components of a system have been taken at a reference date, they are used to create probabilistic projections of the system's performance over the short term to serve as operation guidelines and to facilitate the regular monitoring of the system. A large number of synthetically generated flow sequences are used for simulation of the system performance, all based on the same operating rules as determined for the decision period under consideration. Projections of the storage state of all the reservoirs in the system are then produced in graphic form. As time progresses, the real storage state of each reservoir, as well as of the total system, are plotted on these graphic projections. This provides a clear and unbiased indication of whether the system is entering deeper into a drought situation or whether it is actually recovering. Based on the regular monitoring of the system, timely decisions can be made to lift water restrictions, should the situation ease, or to increase curtailments, should the situation worsen.

Figure 6 gives a typical example for the Vaal River System when the total monthly storage in the system was projected at the beginning of May 1993. The actual storage in the system from May 1993 to May 1994 was plotted on this projection as time progressed. The coloured circles indicate the storage levels below which water restrictions will have to be introduced.

Figure 7 shows the simulated trajectories of reservoir storage for 201 synthetic streamflow sequences, with box plots of the cumulative distribution function superimposed thereupon. Also depicted in this figure is the possible rate of change in reservoir storage that can be expected for the different months and seasons.

PLANNING FOR THE FUTURE

A key feature in planning the development of water resources in South Africa is to evaluate the *future performance of the system under dynamic growth conditions*, simulating the actual operating and water restriction rules that could be used, as described in the previous section.

The phasing of new projects into a system, as well as the warm-up periods that are required for new dams, must be aimed at preventing the system from exceeding selected levels of risk of water restrictions. The phasing of new schemes is extensively analysed by using synthetically generated flow sequences to capture possible future drought events. Figure 8 shows the probabilistic supply capability of the Vaal River System after the scheduling of some future augmentation schemes, against the background of the projected growth in demand.

The probabilistic management of complex water resource systems, as introduced in this chapter, is comprehensively covered by Basson *et al* (1994).

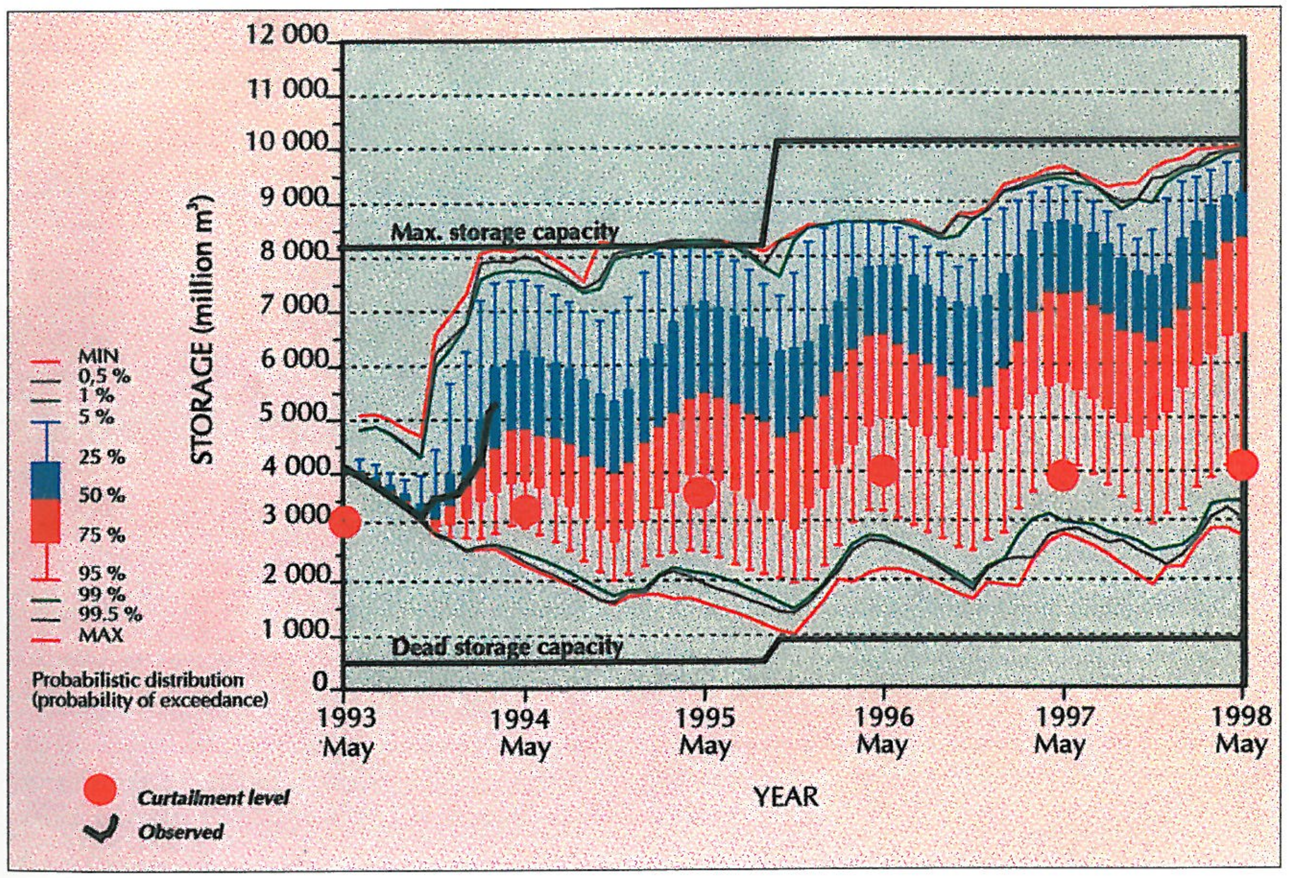


Figure 6: Projected storage for the Vaal River System

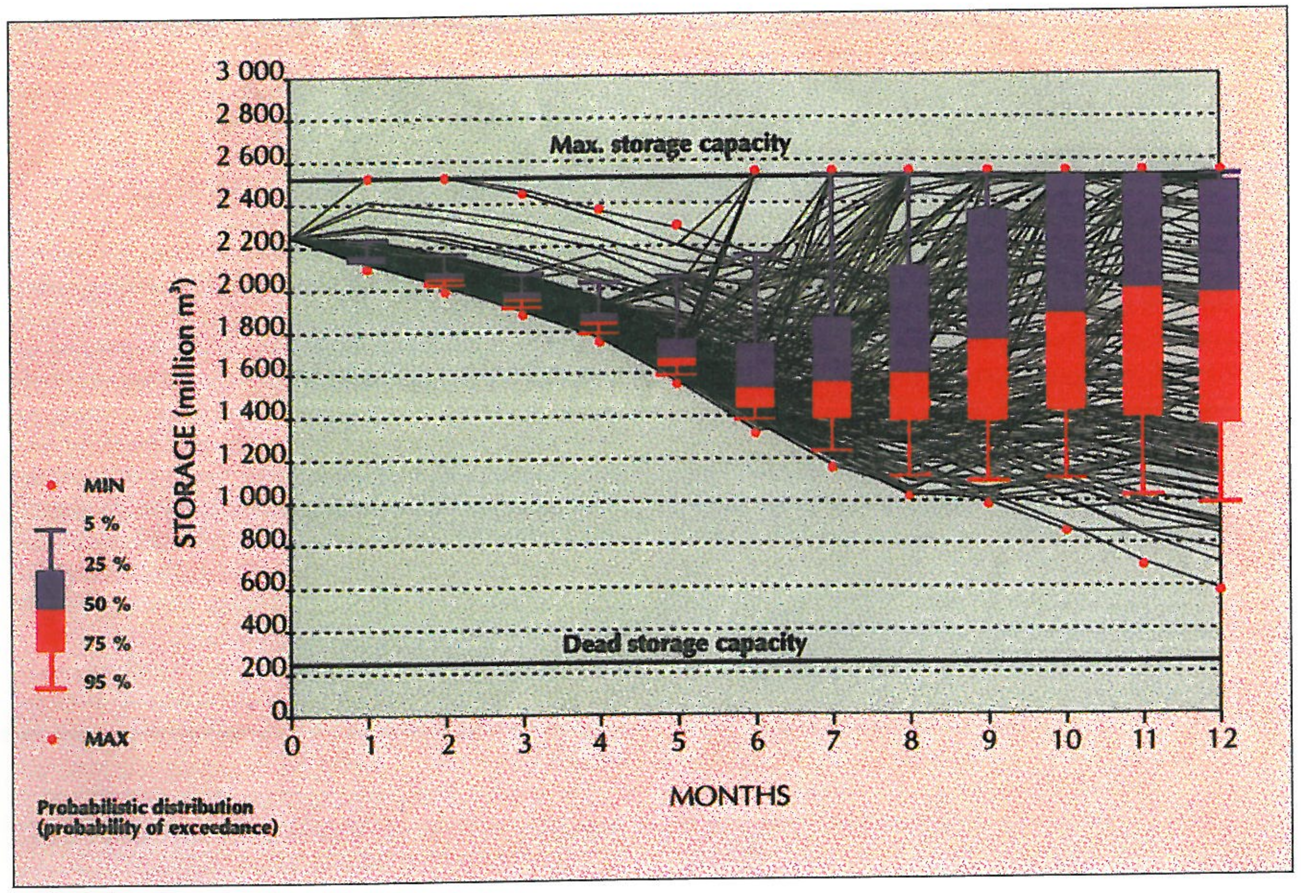


Figure 7: Traces of possible reservoir trajectories

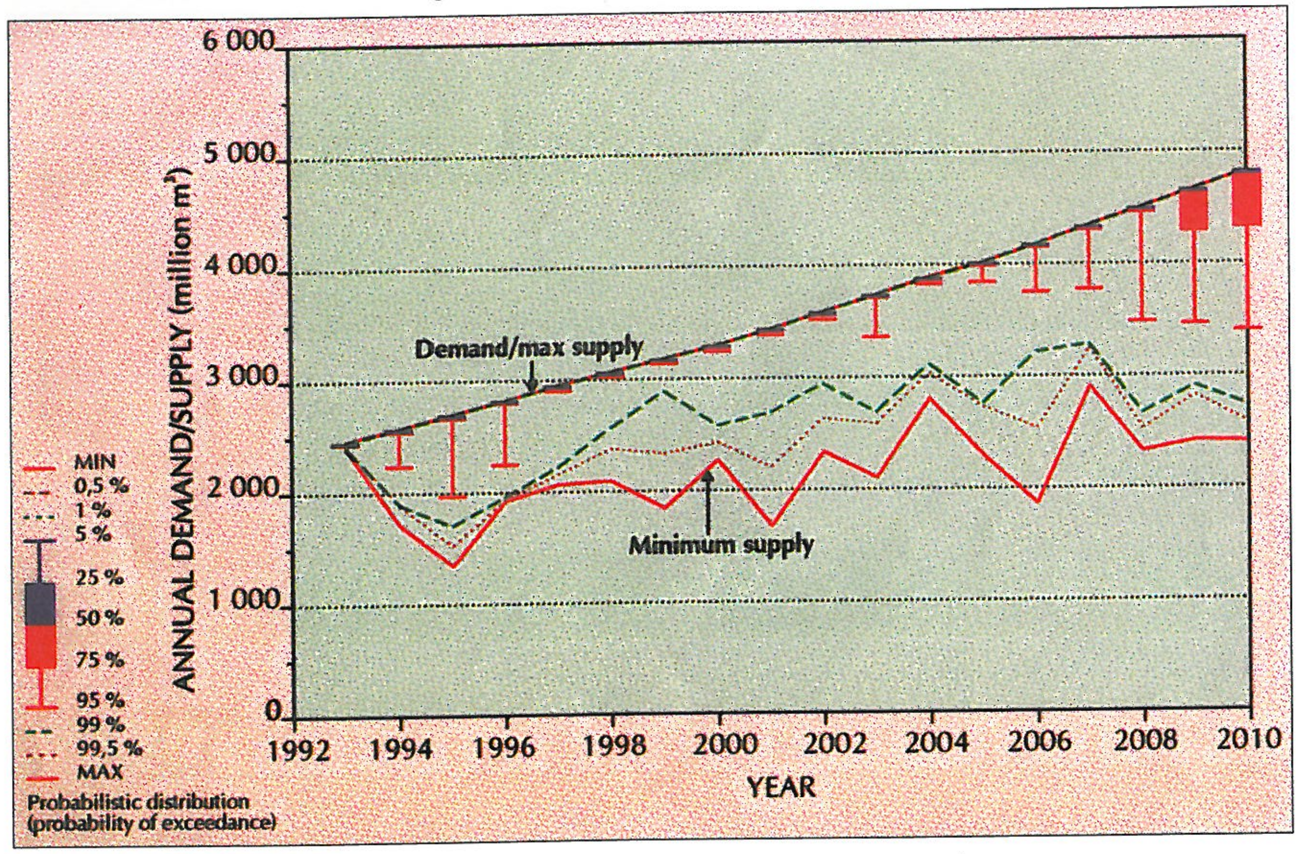


Figure 8: Supply capability under a scenario of growing demand

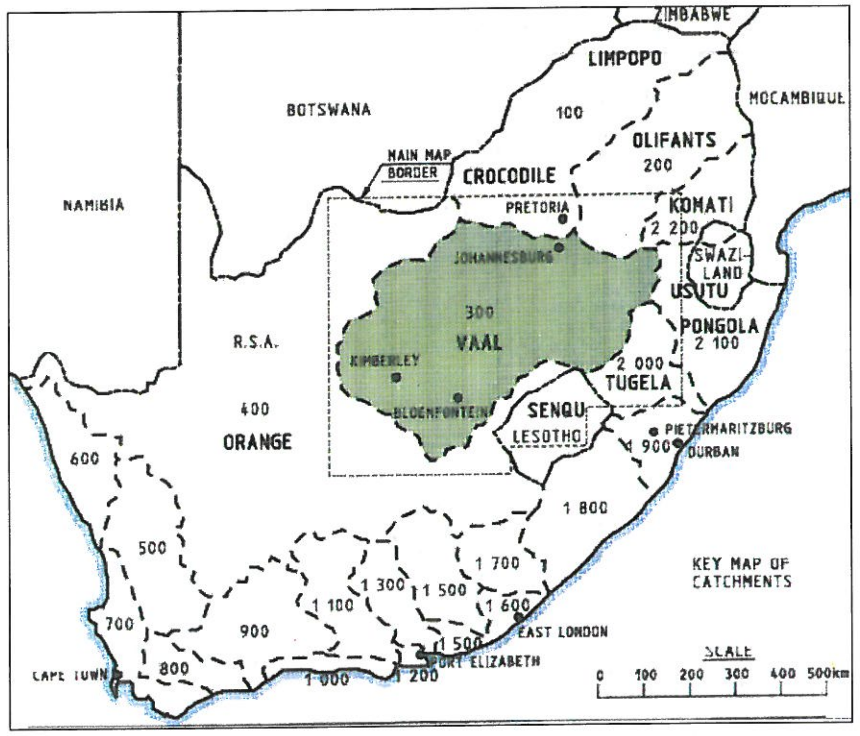


Figure 9: Main catchment areas of South Africa showing the Figure 2 map border

REFERENCES

Basson MS, Allen RB, Pegram GGS and Van Rooyen JA (1994). *Probabilistic Management of Water Resource and Hydropower Systems. Water Resources Publications.* Colorado, USA.

Basson MS, Triebel C and Van Rooyen JA (1988/1989). *Analysis of a multi-basin water resource system: A case study of the Vaal River System.* IWRA VIth World Congress on Water Resources. Ottawa, Canada

Basson MS and Van Rooyen JA (1989). *The integrated planning and management of water resource systems.* 4th SA National Hydrology Symposium. Pretoria

McKenzie RS and Allen RB (1990). *Modern water resource assessment techniques for the Vaal System.* Proc of the Institution of Civil Engineers Part 1, vol 88: 995-1014. London

Pegram GGS and McKenzie RS (1991). *Synthetic streamflow generation in the Vaal River System.* Trans SA Inst Civ Eng

South Africa, Department of Water Affairs (1986a). *Management of the water resources of the Republic of South Africa.* Pretoria

South Africa, Department of Water Affairs (1986b). *Yield analysis and terms and procedures.* Report P C000/00/6886 by BKS Inc. Pretoria

South Africa, Department of Water Affairs (1991). *The determination of the economic value of water for the Vaal River System Area.* Report P C000/00/10291 by Urban Econ. 1991

Van Niekerk PH and Basson MS (1993). *Practical experience in the probabilistic based management of large water resource systems.* ASCE Symposium of Engineering Hydrology. San Francisco, USA

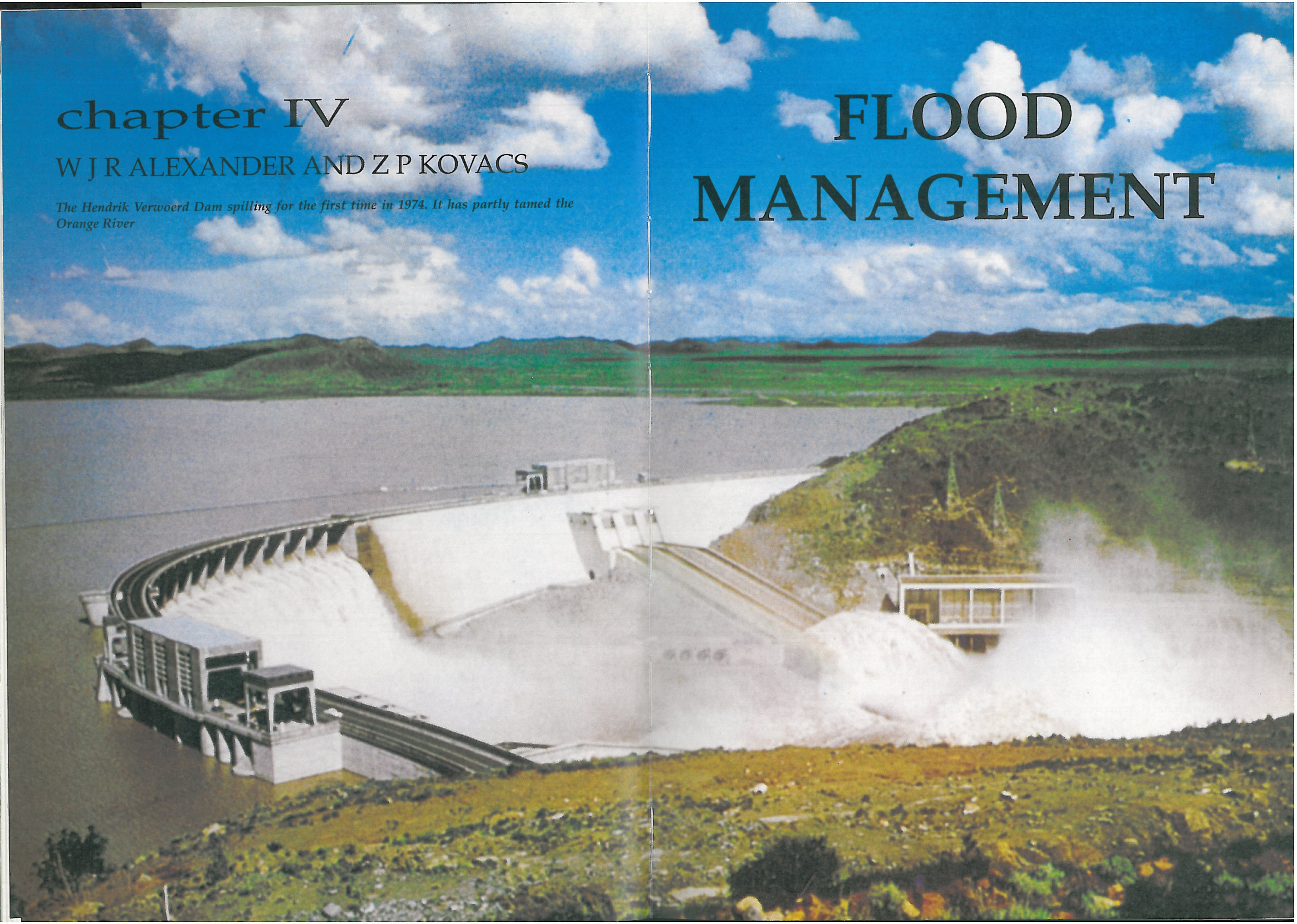
Van Robbroeck TPC (1979). *Inter-basin water transfers in South Africa.* The Civil Engineer in South Africa, vol 21(2): 29-35

Van Rooyen JA and Basson MS (1992). *System analysis in water resources management.* Proc of the SA National Water Week Conference. Pretoria

chapter IV

FLOOD MANAGEMENT

W J R ALEXANDER AND Z P KOVACS



The Hendrik Verwoerd Dam spilling for the first time in 1974. It has partly tamed the Orange River

FLOOD MANAGEMENT

by W J R Alexander

South Africa has a long history of severe floods, particularly in Natal in the north-eastern quadrant of the country. The following is an extract from one of the earlier documents:

Government Notice No. 86, 1869
His Excellency the Lieutenant Governor directs the publication for general information of the subjoined report of the Commission appointed to enquire into the causes of the destruction of certain Bridges in this Colony during the Flood of August, 1868. This report has been laid on the table of the Legislative Council.
By His Excellency's command,
D ERSKINE,
Colonial Secretary,
Colonial Office, July 14, 1869

The report mentions "the great flood of 1856", which occurred twelve years earlier and remains the highest recorded flood along the central coastal area of Natal.

In 1919 the Department of Water Affairs (then Department of Irrigation) issued the first paper on *Maximum Flood Curves* in its Professional Paper series on design practice in the Department. In his foreword AD Lewis, then Director of Irrigation, wrote:

Too much importance must not be attached to the formula. No formula is likely to be discovered which will apply to all drainage areas. The maximum flood depends on too many uncertain circumstances, such as intensity of rainfall, size and shape of catchment and channel, and permeability of ground surface.

In 1945 Justin, Creager and Hinds published their three-volume series *Engineering for Dams*, which was widely used in South Africa and elsewhere for dam design. An empirical flood formula based on an upper envelope of observed maxima was presented with the following caution:

Possible Future Peaks

In making use of records of maximum recorded floods on rivers in a given district to estimate the expected peak discharge at a given place, it must be remembered that what has occurred in the past must surely be exceeded in the future.

These two pithy comments are as true today as they were when they were published. Despite the collection of a vast amount of hydrological data and several decades of international research, there is still no universally applicable method for flood magnitude estimation for dam design. Like the annual Paris fashion shows, new methods were developed over the years and were enthusiastically applied. When experience showed that the method was flawed, an alternative method was proposed and applied, and the cycle continued. In South Africa the cycle started with empirical methods based on upper envelope values of recorded floods and continued with empirical-probabilistic methods based on the Hazen distribution, deterministic methods based on the unit hydrograph method, and direct statistical analysis methods as longer records became available.

More recently there has been a return to an empirical method based on upper envelope values of observed maxima proposed in 1918, thereby completing the 75-year cycle. The empirical method proposed in 1918 was replaced by the empirical-probabilistic Roberts method in the 1960s.

Damaging floods in 1959 in Natal initiated the establishment of the Hydrological Research Unit at the University of the Witwatersrand in Johannesburg, funded by the South African Institute for Civil Engineers. The research culminated in the publication of the manual *Design flood determination in South Africa* in 1969, one hundred years after the Colonial Office report (Midgley, Pullen and Pitman, 1969). The emphasis was on the unit hydrograph method and included a method for determining the probable maximum flood. Solution methods were based on graphical analyses.

Four severe, widespread flood events occurred in 1981, 1984, 1987 and 1988. There was widespread loss of life and destruction of structures, and once again the validity of current analytical methods was questioned. One irate reader wrote a letter to the editor of a local newspaper:

I don't care a damn whether or not a degree in accountancy, engineering, medicine or anything else is recognised in foreign nations to the north of us. All I want is an accountant who can keep the Receiver off my back and look after my investments. All I want is a civil engineer who can build better bridges than the ones that are always washed away when there are floods in Natal.

In 1988 the South African National Committee on Large Dams commissioned the publication of the handbook *Flood Hydrology for Southern Africa*, which was published in 1990 (Alexander, 1990a). A deliberate decision was made NOT to specify a particular method. The following message appeared prominently on the first page of the publication:

The first and most important lesson to be learnt from this handbook is that there is no single calculation method that is better than all other methods under all the wide variety of flood magnitude determination problems that will be encountered in practice. Consequently you will have to apply your own experience and knowledge to your particular problem. The rest of this handbook will assist you in developing or expanding your knowledge; the case studies will help you develop your experience; and the computer programs will provide a tool for rapidly exploring a wide range of solutions — something that is seldom possible with the more laborious, time consuming and consequently more costly hand calculation methods.

The computer programs distributed on a disk together with the handbook were also applied in subsequent research which concentrated on a reappraisal of all methods for determining the flood magnitude-frequency relationship, and the development of methods for specific applications.

RECENT SEVERE FLOODS

The severe floods that have occurred in South Africa since 1981 have all produced the highest floods on record in some catchments.

The rainfall patterns produced by three quite different weather systems are shown in Figure 1. The region affected by the 1987 floods overlapped the 1984 region and is not shown for clarity.

Some features of general interest arising from these floods are given below.

Laingsburg floods of January 1981

Laingsburg lies in the arid Karoo region 250 km north-east of Cape Town on the main road and rail routes to the interior. The Buffels River overtopped its banks at 10:00 on Sunday, 25 January 1981, and reached its peak eight hours later, during which time it traversed five street blocks. This would normally have been more than enough time to warn and evacuate most of the people in this small community; nevertheless 104 persons drowned. The Floriskraal Dam 20 km downstream of Laingsburg did not fail, despite the water level rising well above the non-overspill crest of the dam. A search for evidence of palaeoflood levels downstream of the dam was successful, but these were LOWER than the 1981 flood. Elsewhere in South Africa palaeoflood levels are often appreciably higher than recent flood levels.

Floods caused by the tropical cyclone Domoina in January 1984

The cyclone crossed the mainland coast near Maputo in Mozambique, followed a curved path

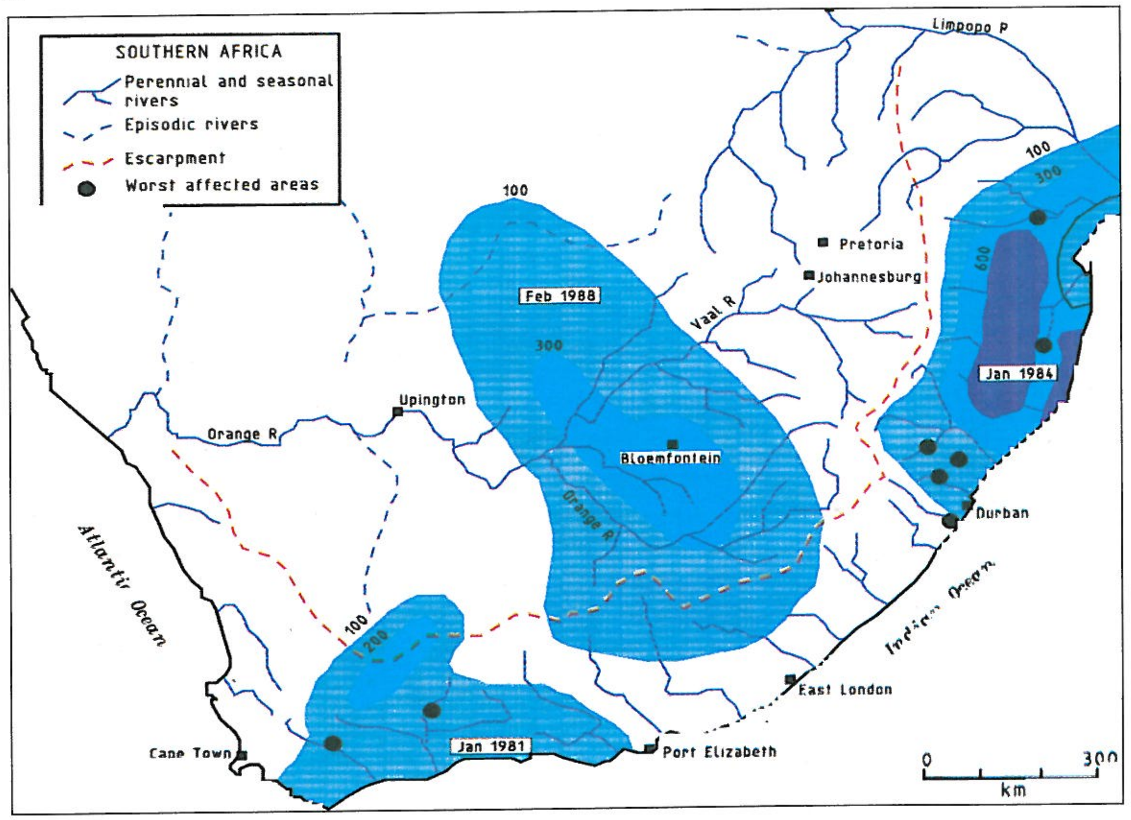


Figure 1: Main river systems and areas affected by recent floods. Dots show the eight selected stations of long record used for Figure 2 data.

and exited out to sea in northern Natal three days later. The path of the cyclone in Natal was in a downstream direction, which increased the magnitude of the floods. The relatively greatest flood peaks ever recorded anywhere in South Africa occurred in the Mfolosi River catchment. The loss of life and damage to structures would have been even more severe if the path had been across the more densely populated area further to the south. This is the first recorded tropical cyclone to have crossed into South Africa, although a number of previous tropical cyclones approached close enough to cause widespread rainfall and floods.

Natal floods of September 1987

In many catchments these floods were the highest on record, exceeded only by the 1856 floods (where this information was available). Not only did these floods cause severe damage and loss of life; they also destroyed the main water pipelines to Durban where water had to be rationed until repairs were completed. An encouraging feature was the accuracy of the forecasts issued four days in advance of the rainfall and five days before the occurrence of the floods.

Floods over the interior in February 1988

The floods in many catchments were the highest on record. Two large dams failed but there were no lives lost from this cause. This was because, by the time the dams breached, the downstream areas and bridges were already under water. These floods occurred five months after the earlier floods in Natal and were followed a month later by further floods. Prolonged seasonal rainfall is a characteristic of severe flood events.

Floods in urban areas

Smaller scale severe storms have also occurred in urban areas:

September 1968	Port Elizabeth	552 mm in four hours
August 1970	East London	447 mm in six hours
January 1978	Pretoria	245 mm in four hours

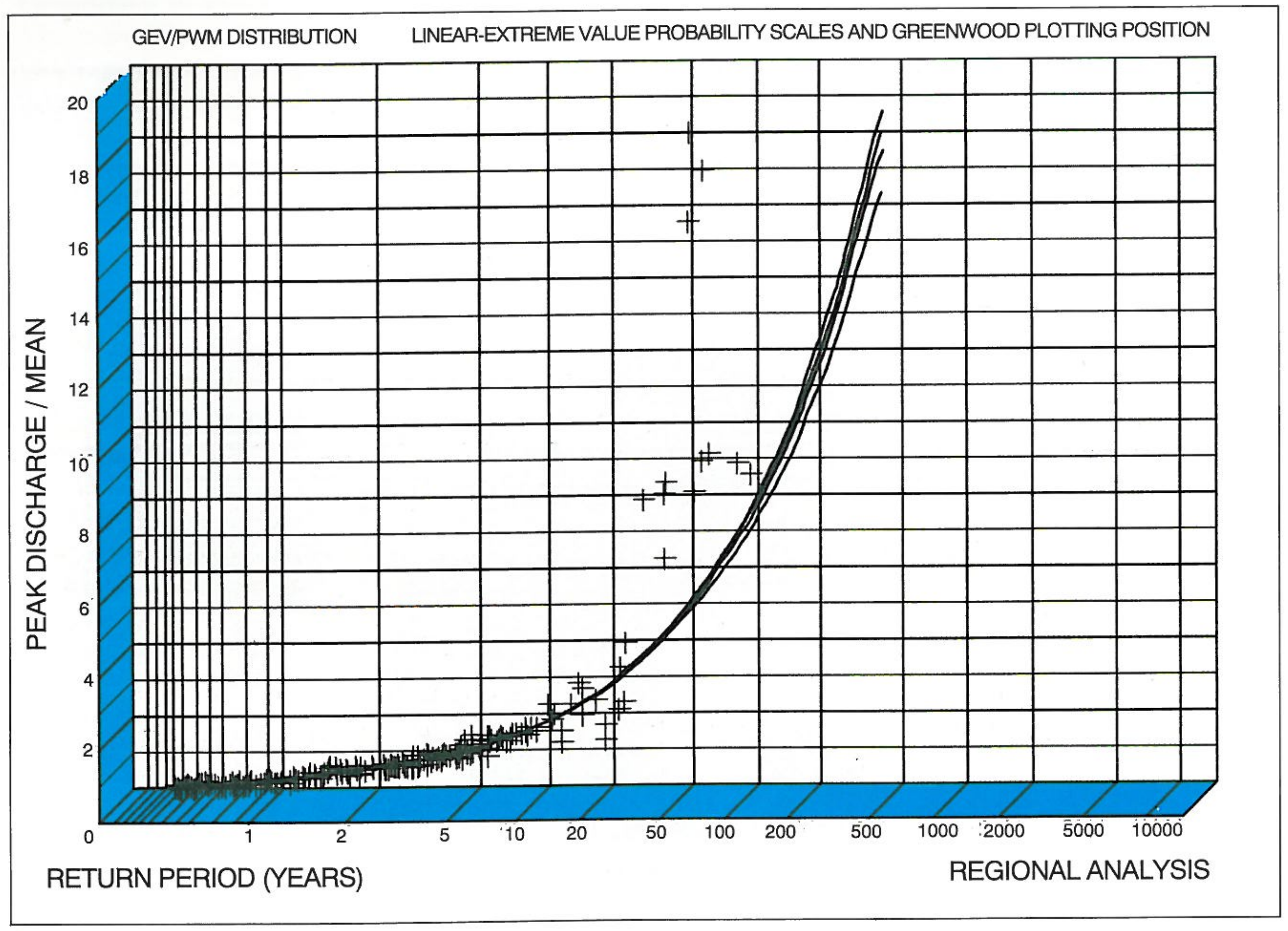


Figure 2: Probability plots for eight selected stations (shown as dots on Figure 1)

Damage and loss of life were not of the same scale as in the large area floods detailed above, but since then there has been an appreciable increase in residential occupation of flood plains in the major urban areas in South Africa, thus a repetition of storms of this magnitude in any major urban area in the future could result in an appreciable loss of life.

The probability plots of data from eight selected widely dispersed sites with a combined record length of 288 station years are shown in Figure 2. The locations of the stations are indicated in Figure 1 above. The flood magnitude-frequency relationships are remarkably similar despite topographical and climatological differences. The anomalous high values are each the result of sound methods of measurement, and they were supported by other information. The weather systems that caused these high values have been identified in most cases. While it is clear that these values cannot be ignored in statistical analyses, an extrapolation of the flood magnitude-frequency relationships to long return periods gives unrealistic results. Methods for overcoming this difficulty have not yet been developed.

TOPOGRAPHY AND CLIMATE

The main feature of South Africa is the 1 500 m high interior plateau which is drained by the westward flowing Orange-Vaal river system to the mouth of the Orange River on the Atlantic coast. The rivers on the plateau are separated from the southerly and easterly flowing coastal rivers by the high escarpment, which has a maximum elevation of 3 480 m north-west of Durban.

The northern region of the country receives 90% of the annual rainfall in summer, compared with 10% in the areas in the south-west. The mean annual rainfall is highest in the eastern and southern escarpments where it exceeds 3 000 mm, and lowest in the arid western regions where it is less than 100 mm. River flow regimes vary from perennial through seasonal to episodic. In the arid areas there may be no flow at all for a number of years. The flood-producing weather systems also vary over a wide range, from tropical cyclones in the north-east to cut-off low-pressure systems east and south of the escarpment and tropical/temperate wave interaction systems (*Botswana lows*) over the interior.

Some details of the rain produced by the weather systems that caused recent severe floods are given in Table 1. Note the diverse geographic locations of the weather systems in Figure 1, and the similarity of the rainfall properties of the 1984 and 1987 events in Table 1 despite altogether different weather systems.

SEVERE FLOOD-PRODUCING WEATHER SYSTEMS

Tropical cyclones

The properties and regions of occurrence of *tropical cyclones* (called *hurricanes* and *typhoons* elsewhere) are well known. Most of those that affect Southern Africa are generated in the Indian Ocean to the east of Madagascar, although some develop in the Mozambique Channel between Madagascar and the mainland. They only rarely cross the continental coast. The tropical cyclone Domoina of January 1984 was an exception and is the only recorded cyclone to penetrate the interior of South Africa and exit again further south.

Of the 17 cyclones that entered the Mozambique Channel during the period 1950 to 1988, ten pro-

Table 1. Rainfall produced by recent severe weather systems

Date	Jan 1981	Jan 1984	Sep 1987	Feb 1988
Weather system	Cut-off low	Tropical cyclone	Cut-off low	Botswana low
Point rainfall (mm)				
one day maximum	230	615	577	187
storm maximum (days)	288(3)	906(3)	902(3)	425(5)
Areal rainfall (km^2)				
area receiving >200 mm	N/A	94 000	69 000	31 500
area receiving >500 mm	none	18 500	14 400	310
area receiving >700 mm	none	1 750	1 600	none

duced heavy rainfall over parts of South Africa and only one traversed the mainland. The meteorological and hydrological aspects of the tropical cyclone Domoina in 1984 are described in Kovacs *et al* (1985).

Reliable numerical prediction models are in operation. The track and development of tropical cyclones can be forecast with sufficient accuracy for flood-warning purposes. The efficiency of prediction models was demonstrated in the USA in August 1992, when the hurricane Andrew caused widespread devastation and became the costliest natural disaster to have occurred in the USA. Owing to early warnings and efficient evacuation procedures the loss of life was minimal.

Cold fronts and cut-off low-pressure systems

Cut-off low-pressure systems are the major flood-producing weather systems in South Africa. An anticyclonic disruption develops when a strong upper ridge advances south-eastwards south of the continent, isolating a cold upper pool over the western parts of South Africa. This high advects large amounts of humid maritime air over the southern and eastern seaboard. At the same time a low-pressure system develops over the central interior in conjunction with the upper cut-off low. This results in the southward and upward advection of moist tropical air over the inland areas. The presence of all of these factors results in widespread rainfall over the interior (Taljaard, 1985).

The meteorological aspects of the 1981 floods are described by Estie (1981) and the hydrological aspects by Kovacs (1982).

The September 1987 floods in Natal were another example of severe floods produced by this weather system. Meteorological aspects are described in Triegaardt *et al* (1988) and the hydrological aspects in Van Bladeren and Burger (1989). Tennant and Van Heerden (1993) demonstrated that the orography of the high Drakensberg escarpment played an important role in the development of the system and the production of high intensity rainfall.

These systems are all associated with large amplitude mid-latitudinal pressure systems. Numerical weather prediction models are able to model these with considerable success for up to five days ahead. These models are improving rapidly and a new generation of regional models will probably be able to provide better prognoses of the area and duration of heavy rainfall. A recent example was the successful prediction of the heavy rainfall that resulted in the September 1987 floods in Natal four days in advance of its occurrence (Triegaardt *et al*, 1988).

Tropical/temperate wave interaction

The February 1988 floods over the central interior of South Africa were caused by a near stationary hemispheric four-wave pattern in the upper atmosphere, which maintained a steady southward advection of moist, tropical air. A stationary zone of heavy rainfall was sustained for four days over a 250 km wide band stretching south-eastwards from Botswana to the south-east coast. This caused severe damage, particularly to internal road and rail communication routes. The meteorological aspects are described in Triegaardt, Van Heerden and Steyn (1991) and the hydrological aspects in Du Plessis *et al* (1989).

These systems represent the interaction between tropical and temperate weather systems, but are also dependent on mesoscale cloud systems to initiate and anchor the weather systems in one place. They only develop where surface conditions and tropical air movement over South Africa have been maintained over a long period. Because of the importance of small-scale processes, numerical methods have been less successful in predicting the possibility of heavy rainfall. New regional models hold promise for accurate 24-hour prognosis.

Other observations

The number of weather systems that caused widespread rainfall events during the past 34 years are shown in Table 2.

Table 2. The occurrence of widespread rainfall events in the past 34 years.

Cold fronts	22
Cut-off low-pressure systems	29
Botswana low-pressure systems	3
Tropical cyclones	8
Total	**62**

The country-wide frequency of these widespread rainfall events is about two events per year, but not all of these events have caused serious floods. In any one catchment the frequency is one event in a number of years. The combination of severity and rarity results in the anomalous high outliers in the frequency plots seen in Figure 2 above.

The following are some general observations based on wider studies of floods in South Africa:

- Floods that cause severe damage are often the result of storm rainfall covering a much larger area than that of the individual catchments, and durations much longer than the catchment response times.
- These widespread, severe rainfall events often occur within seasons of above average rainfall and are often preceded by moderate rainfall over the previous days, weeks or months.
- There is some evidence of global synchronous occurrence of seasons of extreme floods and droughts.
- There is an apparent non-random grouping of years of above and below average rainfall on a sub-continental scale.

The meteorological and hydrological characteristics of these floods are well documented. The loss of life and wide-scale damage caused by the floods resulted in a number of investigations, research projects, and a review of the national flood management policy, several of which are still in progress.

ANALYTICAL METHODS

The recent floods destroyed many major structures, including two large dams, many bridges and hundreds of minor structures. Hundreds of lives were lost, and there was wide-scale interruption of communication and services. This led to a critical review of the analytical methods used in hydrological analyses.

Most current analytical methods were reviewed and computer implementations were provided in the handbook *Flood Hydrology for Southern Africa* (Alexander, 1990a). Algorithms were included in the direct statistical analysis methods to allow regionalisation of the distribution parameters, as well as conditional probability and retrofitting adjustments to accommodate zero flows and gaps in the record, together with historical and palaeoflood maxima.

Rainfall-run-off models

By the onset of the 1990s the average length of observed records of annual flood maxima was more than 30 years, with some reliable records giving 80 years' data. There was little doubt that direct statistical-analysis methods using regionally weighted parameters were more reliable than the deterministic unit hydrograph and rational methods when applied to gauged sites. Studies by Alexander and Van Heerden (1991a, 1991b) identified shortcomings in the deterministic methods, particularly in the results for return periods exceeding 20 years. The main reason for the underestimation was the underlying assumption in these methods that the return period of the design flood peak was the same as that for the rainfall. This assumes that the catchment has an undefined average moisture status prior to the rainfall. However, severe rainfall events usually have durations well in excess of the catchment response times, with the result that antecedent catchment moisture status also increases with increase in storm severity. In semi-arid and arid climates the antecedent moisture status varies over a much wider range than in more humid climates, and plays a much greater role in the rainfall run-off process.

The century-old rational method is alive and well in South Africa. The South African version which has been in use for the past two decades has the formulation $Q = C\ I\ A$, where C = catchment coefficient, I = rainfall intensity, A = catchment area.

The South African version of the unit hydrograph method has been in use since its development in 1969 (Midgley, Pullen and Pitman, 1969). Each method has its group of adherents. The unit hydrograph method becomes unstable for small catchments, whereas the rational method is used for catchments of any size.

Computer applications for both methods have been developed and comparisons can be made with the results of direct statistical analyses at sites where long records are available. Algorithms have been incorporated in the deterministic models which allow them to be calibrated against direct statistical-analysis methods applied to sites with long records in the vicinity.

Direct statistical-analysis methods

The severe floods of the 1980s produced many peaks that were the highest on record and appreciably higher than previous maxima. They appear as single outliers when plotted, but cannot be considered as anomalous results. From a design point of view it would be most unwise to ignore them or to assume that they are chance occurrences with long return periods. On the contrary, there is mounting evidence that the widespread rainfall events which cause severe floods are more frequent than has been previously assumed.

Four direct statistical-analysis methods are currently in use in South Africa. They are:

- Log normal distribution using conventional moment estimators LN/MM
- Log Pearson Type III distribution using conventional moment estimators LP3/MM
- General Extreme Value distribution using probability weighted moments GEV/PWM

- Wakeby distribution using probability weighted moments WAK/PWM

The LN distribution has two parameters, the LP3 and GEV distributions each has three and the WAK distribution has five parameters. There is no meaningful difference between the results obtained when using the three- and five-parameter distributions at sites where there are no anomalies in the records. In particular, the GEV and WAK distributions in most cases produce very similar results.

All distributions including those using probability-weighted moment estimators are sensitive to anomalous high and low values in the data set. Low values introduce negative skewness which may not be characteristic of the distribution and may result in an underestimation of the flood peak. One of the reasons for low values is the effect of upstream storage and abstractions which significantly reduce river flow during dry years. This effect is hidden in the conventional linear-EV1 plots but is clearly discernible in graphs with logarithmic scale plots. If the interest is in flood magnitude estimation, these anomalous low values have to be removed or corrected.

The same reasoning does not apply to anomalously high values which are of direct interest in flood magnitude estimation.

Shortcomings in single-site analytical methods

Widespread, severe floods are caused by weather systems that are not annual events in any one catchment, and the magnitudes of the floods caused by these events are often appreciably higher than the next highest values. As can be seen in Figure 2 above, the resulting floods are not part of the same population as the rest of the annual maxima. This poses analytical problems in the determination of the flood magnitude-frequency relationship.

Direct statistical analyses using the methods and computer programs of Alexander (1990a) show that the mixed population analytical method using the five-parameter WAK distribution does not solve the problem posed by these high outliers. There is no evidence to suggest that the four-parameter two-component extreme value distribution will be successful either. These difficulties may seem to reinforce the views of those who have more faith in rainfall-runoff models than methods based on direct statistical analyses. However, the depth-area-duration-frequency relationship of the rainfall used in the rainfall-runoff models is equally suspect.

The South African practice to determine long return period design floods is moving towards empirical envelope methods rather than away from them, despite or possibly because of the increase in knowledge and increase in the lengths of rainfall and river flow records (Kovacs, 1988).

There has been some criticism of these empirical methods: *the failure of flood envelope methods to take explicit account of catchment factors (other than AREA) is seen by some as a sign of scientific bankruptcy* (Beran, 1981 in Reed and Field, 1992).

Two of the analytical methods that have been in use in South Africa and elsewhere for many decades have a similar form:

$$Q_{max} = C\,A^{x} \qquad (1)$$

where A is the area of the catchment and C and x are derived empirically, and the well-known rational method, as given in the formula

$$Q_T = C_T\,I_T\,A \qquad (2)$$

where I_T is the precipitation intensity for a return period T and where the coefficient C_T is also dependent on the return period T.

The two factors that determine the magnitude of a flood at a site are the size of the catchment and the intensity of the rainfall on the catchment. The intensity is a depth-time relationship in which the time component is determined from the length and slope of the main channel. For the calculated catchment-response time the rainfall depth is determined from the rainfall *depth-area-duration-frequency* relationship. Thereafter the effective rainfall is determined by subtracting rainfall volume losses which are assumed to be ascribable owing to infiltration, evaporation, pondage and channel storage.

Only the trunks of the major rivers in South Africa have catchment-response times longer than two days and catchment areas larger than 20 000 km^2. Weather systems that produce severe, widespread floods have durations that are well in excess of the response times for most catchments. With soil cover approaching saturation and rivers already full, the infiltration and storage losses are minimal and the effective rainfall equals the actual rainfall.

In this situation the only remaining variable which controls flood magnitude is the size of the catchment. Consequently, there are theoretically sound reasons for using the simple relationships in these two equations in estimating long return period floods.

Another variable in the unit-hydrograph method is the shape of the unit hydrograph, which is assumed to be a characteristic of the catchment being studied. However, hydrograph shape is a function of rainfall duration. As mentioned above, the duration of rainfall generated by the severe weather systems is typically much longer than the catchment response times, which results in a larger volume/peak ratio than that used in the design procedures.

Our analyses have shown conclusively that the more complex unit-hydrograph method is no better than the simpler rational method, and that both of them are less reliable than direct statistical analysis methods at gauged sites (Alexander, 1990b).

Multiple-site analytical methods

The probability that widespread damage, loss of life and interruption of communications will be caused by floods generated by a single rainfall event cannot be determined with confidence from statistical analyses of river flows within a region. This is largely because of the uneven geographical distribution of gauging stations, different catchment sizes and different lengths of record. The only alternative is to base the analyses on rainfall records. The rainfall properties of interest are the three variables, depth, duration and area. An important additional property is the *direction and rate of movement (or stationarity)* of the weather system. For example, movement is essential for sustaining tropical cyclones (1984 example), whereas stationarity is essential for sustaining rainfall caused by *tropical/temperate wave interaction* systems (1988 for example).

A multivariate extreme-value analysis of the large rainfall data set posed insurmountable problems, as shown by the difficulties hydrologists have in developing much simpler bivariate extreme-value relationships between flood peaks and flood volumes. This relationship is required for routing the design flood through a reservoir to determine the flood-peak attenuation. This should be a simple analytical exercise, but there is very little information in the literature on procedures which involve direct statistical analysis methods. We believe that this is because of the inappropriateness of the *annual exceedance probability* as a criterion in determining realistic combinations of flood peaks and volumes for a specified design flood.

The analysis based on rainfall data can be made more tractable by ignoring storm movement and using fixed geographical regions and fixed durations. Rainfall depth is the only remaining variable. Two data sets were prepared and analysed. These were four-day rainfalls within fifteen geographic regions, and monthly rainfalls within 93 standard rainfall districts. The essence of the analysis of the first data set was a classification algorithm where five *wide-area rainfall* classes of increasing severity were specified. The criteria used in the two sets of analyses are summarised in Table 3.

Each combination has its advantages and disadvantages. The four-day rainfalls can be directly associated with the causative weather systems, but statistical analysis is difficult because the dependent variable is the *number of occurrences* of each of five classes of rainfall events in each region. The dependent variable in the second set of analyses is the monthly rainfall, which is amenable to conventional statistical analysis as well as areal and serial correlation studies.

The results of the studies are detailed in Alexander (1993). They include the preparation of monthly rainfall maps and catalogues for the period 1921 to date, which are useful reference material for estimating vulnerability to widespread interruption of road and rail communications and flood management policy development. These methods were also used to estimate of the severity of the 1991-92 drought.

The results of the first set of analyses provided answers to many of the questions we had asked regarding the severity and areas of occurrence of *large-area, severe-rainfall* events, and why bridges failed with greater frequency in Natal than in the interior despite the application of the same design standards (Alexander and Van Heerden, 1991a).

The correlation analyses using the second data set produced surprising results that will be useful for future applications. In most correlation analyses the full data sets are used, as statisticians usually frown on the use of censored or stratified data. The basis for this objection is the assumption that the data are from a single population. We have already demonstrated that this is not so (Figure 2 above).

Table 3. Data sets used in widespread rainfall analyses

Set number	Space resolution	Time resolution	Dependent variable
1	15 regions	number of occurrences	number of occurences
2	93 districts	1 calender month	monthly rainfall

The interest was in the likelihood that if severe rain occurred in a specific district in a specific month, severe rain would occur in each of the 92 remaining districts in the same month. The period of record was 840 months. Obviously, if the whole record was used there would be a high degree of correlation because half of the record consisted of winter months when there was little or no rainfall in all of the summer-rainfall region. The monthly rainfall depths in each district were converted to the *equivalent exceedance probabilities* for the specific month and district, assuming that the data were LP3/MM distributed. This data set was progressively stratified by increasing the exceedance probability and selecting those months of the record where the rainfall exceeded this value. The rainfall in all other districts during that particular month was used in a conventional correlation analysis.

The number of data pairs decreased with increased stratification, so care had to be exercised in interpreting the results. At first the correlation decreased with increased stratification, but thereafter it increased to the point that there was a consistent, meaningful correlation between districts in the arid western region of South Africa and the more humid regions to the east. The simple conclusion was that it only rains in the arid regions during periods of widespread rainfall over the rest of the country!

The analyses showed that the degree of regional correlation is a function of rainfall severity. This was analytical confirmation of our observations that severe floods are the consequence of *large-area, long-duration rainfall* events, and it has important applications in determining of the risk of large-scale interruption of road and rail communication systems (Alexander and Van Heerden, 1991b).

APPLICATIONS

Research and practice

Possibly because of the wide range of flood-related problems, design specifications are less rigorous in South Africa than in some other countries. One fortunate consequence is that research is not inhibited by the knowledge that improved analytical methods may not be favourably received by practitioners. Indeed, the reverse is the case, and research in the field of flood hydrology has always been strongly user-oriented.

The following are some comments on research and practice in South Africa. The emphasis has since moved from flood hydrology to the broader fields of flood-risk analysis, flood-warning systems and the development of a national flood-management policy. Some highlights of general interest are given below.

A distinction is made between structural failure where the structure is damaged to the extent that it no longer serves its purpose, and functional failure where the structure fails to serve its purpose without necessarily suffering structural damage.

Minor structures

Examples of minor structures are those used in urban drainage works. The total cost of structures in this category is well in excess of the costs of structures in all other categories. Design practice is largely policy-based rather than based on risk analysis or economic optimisation. Because of the high total costs, these structures are usually designed for low return period events, with the consequence of a relatively high frequency of functional failure. Structural failure is relatively infrequent and the repair costs are generally a low percentage of the total annual costs. Functional failure results in inconvenience to the public rather than serious financial or life-threatening consequences.

Research

Most urban-drainage design methods are essentially hydraulic models with hydrological components. The hydrological process assumptions in these models lead to the conclusion that urbanisation increases flood peaks and, consequently, structures should have increased capacities. However, this increase has not been detected in recorded data sets where appreciable urbanisation has taken place during the period of record.

Moderately large structures

Bridges across major rivers are examples of structures in this category. While dams have a much higher potential for causing loss of life and damage, more lives have been lost in South Africa due to the structural and functional failure of bridges than due to the failure of dams. This is largely because of the more stringent safety requirements for dam construction.

Bridge location is determined rather by optimum route location than by optimum foundation conditions. Bridges are built higher above the river beds to reduce the risk of functional failure. However, the higher elevations make them more vulnerable to structural failure when unusually severe floods occur. There has been an unacceptably high number of bridge failures due to floods in recent years, particularly in Natal, but also in the southern Orange Free State-Northern Cape region, and in the southern Karoo. In addition to the direct repair costs, the indirect costs to users have also been severe.

An even more tragic occurrence was the influence of the bridge over the Buffels River at Laingsburg during the 1981 flood. The combination of topography and the location and design of the bridge resulted in an appreciably higher loss of life and damage to buildings in the town than would otherwise have been the case. Sixteen persons trapped on the bridge lost their lives.

In most cases bridges are designed for a high degree of safety as far as the traffic-imposed loads are concerned. However, most designs have until recently made no provision for flood-associated loads other than requiring a specified clearance above the water level reached by a flood during the specified return period. No additional allowance is required for wave action or floating debris. The consequence is that there have been many structural failures due to flood-related loads and very few, if any, failures due to traffic-imposed loads. The risk of failure of a structure due to floods is a function of the *flood magnitude-frequency* relationship and the probable strength (resistance to failure) of the elements of the structure for a range of applied loads.

The determination of the flood-imposed loads on a structure is difficult as it requires a knowledge of the velocity fields for a range of flood magnitudes and of the corresponding loads on the bridge elements. A knowledge of the failure-probability of each structural element for a range of loads is also required for risk analysis. Physical laboratory models may be useful in difficult situations, particularly for crossings of large alluvial floodplains. Computer models are less expensive and can be used to explore a wide range of alternative options, particularly where cost optimisation is an important consideration.

While a full risk-analysis is analytically intractible, simplified assumptions can be made and Monte Carlo methods can be used as exploratory tools. These include the generation of synthetic flood and strength sequences for the principal structural elements for the assumed probability distributions. The method is described by Alexander (1993).

Research

The extensive damage to bridges caused by recent floods gave rise to a co-ordinated multi-disciplinary research programme, which is approaching completion.

Large structures

The most important structures in this category are large dams whose failure could cause serious downstream damage and loss of life. In South Africa, as in most countries, a very high degree of safety is required and there are statutory requirements that have to be met for existing as well as new dams. South African guidelines allow designers to use either the South African version of the *probable maximum flood* (Midgley, Pullen and Pitman, 1969) or the *regional maximum flood* as described by Kovacs (1988). Cost optimisation procedures and flood magnitude-frequency analyses are not permitted in determining of the design flood for high-risk structures. There are some practitioners who question the use of these *ultra-safe* designs.

Research

The results of research on widespread, severe floods are given in a paper by Alexander (1994), at the 18th ICOLD Congress in Durban.

Interruption of communications and essential services

Trunk roads are designed for high-speed, all-weather transportation, which includes heavy haulage vehicles, frequent passenger buses and high densities of private vehicles. The direct and indirect costs of interruption of communication routes due to floods have increased in proportion to the increased use.

Another recent development is the isolation of communities during floods. Large communities have been cut off from hospitals, health centres and places of work during floods. The establishment of informal settlement areas in and near cities and on the flood plains themselves, in some instances, is a matter of considerable present concern. The socio-political consequences of being unable to reach and assist these communities during severe floods, because of the inundation and destruction of roads and bridges, could become serious.

Residential occupation of floodplains

It is estimated that at least 50 000 people, and possibly more than 100 000, are living along rivers and streams in South Africa below levels reached by previous floods. Most of these live in unplanned settlements falling within the jurisdiction of local or regional authorities.

As is the case in many developing countries, South Africa has also experienced a general migration of the rural poor to urban areas and the surroundings. This migration was accelerated by the recent drought. It is often the case that the only vacant land is in flood-prone areas where planned development was prohibited in the past. This is in addition to the many thousands of people living in planned development which is subject to flooding. The low-lying area of Ladysmith in Natal is one of many of these cases. *[In February 1994 a further flood occurred here, the largest in history and as a result a new flood control dam, Mount Pleasant Dam, is being built. Ed.]*

Operation of dams with gate-controlled flood outlets

Owners of dams with gated spillways have to develop operation procedures based on a combination of knowledge of rainfall that has occurred and flows that have been measured in upstream rivers, and estimates based on forecasts of rainfall and resulting additional high flows that may occur in the immediate future. Consequently, it is not possible to ensure that floods will be discharged optimally. Operation procedures have to take this into account.

Flood-warning systems

In most cases where lives are at risk, the only viable means of reducing the risk is through the operation of efficient flood-warning systems. A computer-based *National Flood Advisory Service* has been developed and is now being tested operationally. In addition, further methods are being developed for application by local authorities and small communities.

Three levels of warning are envisaged. At a national level the objective is to make flood-related information available as soon, and as widely, as possible. A computer-based system has been developed and it can be accessed by any authorised person who has access to a telephone, computer and modem. The information includes rainfall for the previous 24 hours recorded at some 500 sites, weather forecasts, the state of storage in selected reservoirs and the discharge in selected rivers. Provision has been made to relay satellite imagery and radar coverage, once this facility becomes available. This is a flood advisory service and not a flood-warning system.

The second level is the action taken by local authorities on receipt of information that floods can be expected. The objective of local authorities is to issue warnings to all persons in threatened areas to watch the water level of the river. Because of legal implications they are not advised to evacuate their premises.

The third and most important level is the development of methods to ensure that all people at risk are fully aware of the danger, and to suggest the action that they should take should floods occur. These systems have been developed and are currently being evaluated operationally (Alexander, 1993).

National flood-management policy

Another consequence of the recent floods was the perceived need to develop a national flood-management policy. Some of the policy issues that are being addressed are the equitable distribution of economic risks and an equitable basis to control development within flood-prone regions.

DROUGHTS AND CLIMATE CHANGE

Droughts over Southern Africa from January to March 1992

The floods of the 1980s were followed by the most severe nation-wide drought on record, which was at its worst during the summer of 1991-92 and continued into 1993 in parts of the country.

In October 1991, minor floods occurred over much the same area of the interior as the February 1988 floods. In some rainfall districts this was the highest rainfall for the month since records commenced in 1921. Within three months, however, the rainfall was the LOWEST on record for the month. The drought over the interior of Southern Africa for the period January to March 1992 was the worst since district rainfall records became available in 1921.

There is some concern that the floods and the subsequent drought resulted from global climate changes that are introducing larger swings in weather extremes, although the evidence for this is still inconclusive.

Climate change

Alexander and Van Heerden (1991a) provided evidence to support the possibility of increase in frequency of flood-producing rainfall in recent years. This is shown in Figure 3. This information, taken together with the severe drought over the past three years, reinforces the view that weather systems are becoming more extreme. It is, however, not possible to determine whether or not these are part of the natural climate variability.

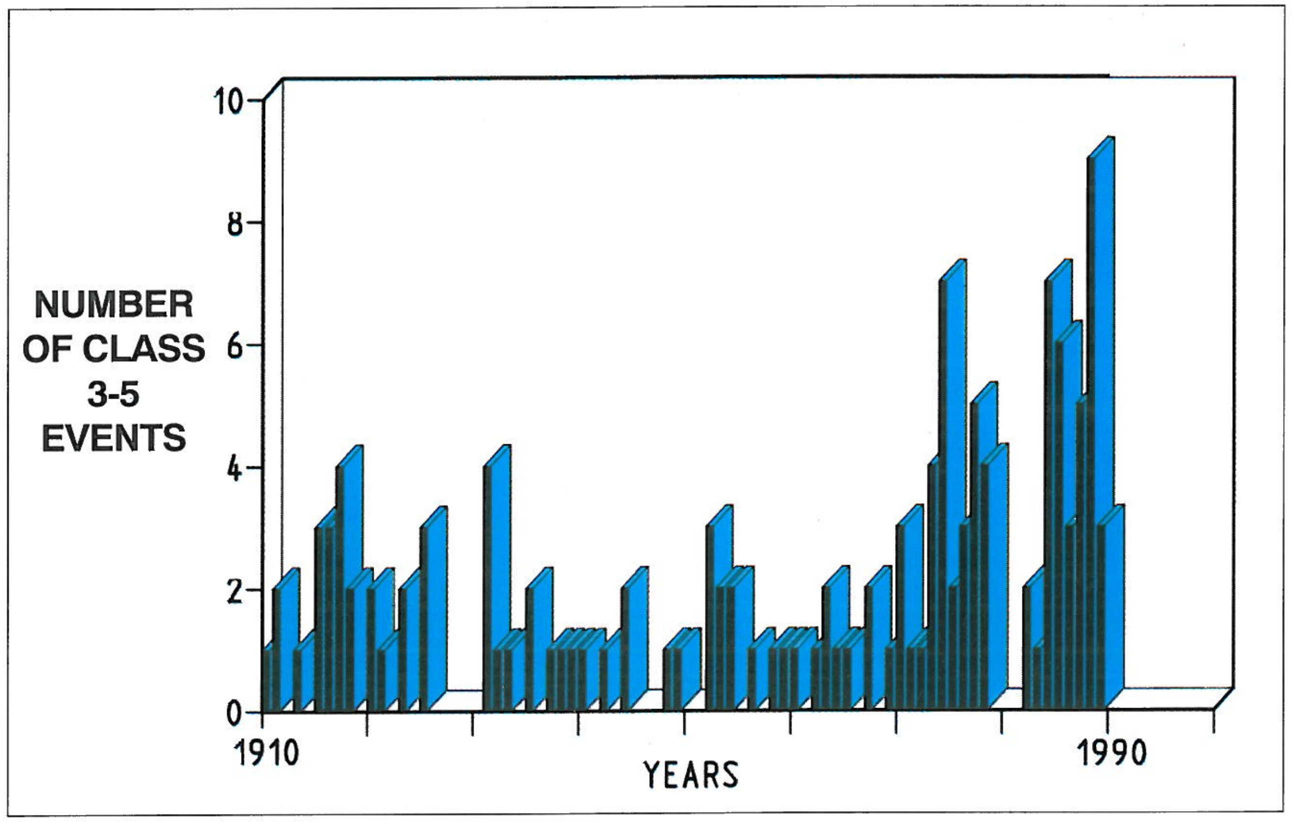


Figure 3: Number of severe rainfall events per year in South Africa from 1910 to 1990

CONCLUSIONS

The occurrence of four recent, well-documented, widespread flood events caused by diverse weather systems in different parts of South Africa has provided valuable information on the deficiencies of analytical methods on the one hand and a greater understanding of the properties of severe, widespread floods and the weather systems that cause these floods on the other hand. The studies continue, with emphasis on the development of flood-warning systems, flood-risk analysis and policy formulation.

[Chapter IV continues overleaf with a discussion on design floods. Ed.]

THE REGIONAL MAXIMUM FLOOD PEAK: A SOUTH AFRICAN APPROACH FOR ESTIMATING MAXIMUM DESIGN FLOOD AT LARGE DAMS

by Z P Kovacs

A realistic estimate of *maximum maximorum* type flood peaks is a must in all those cases where structural failure of a dam, levee or other work could result in deaths and/or catastrophic damage. Even if the potential for a flood catastrophe did not exist the maximum flood-peak estimate could still be useful in providing an idea of the extent of inundation and its consequences.

In current worldwide practice the most frequently applied methods of maximum flood-peak estimation are the PMF (probable maximum flood), derived from deterministic principles, and the 1 000-year to 10 000-year (or even longer) return period flood peak obtained from probabilistic analysis. As to PMF, it often results in grossly overestimated or inconsistent values (Figures 4 and 5).

In the late seventies it became obvious that there is an urgent need to reconsider the long neglected empirical approach, nowadays considered by some, who prefer unproven theories to facts, as *outdated and unscientific.*

THE FRANCOU-RODIER DIAGRAM

The basis for an up-to-date empirical approach was found in the Francou-Rodier diagram of maximum flood-peak estimation shown in Figure 4 which is self-explanatory. The Francou-Rodier equation is

$$Q=10^6 (A/10^8)^{1-0,1K}$$

where Q is the maximum peak discharge in m^3/s, A is the catchment area in km^2 and K is a regional coefficient. The K=constant lines represent flood peak envelopes in hydrologically homogeneous regions.

In Figure 5 world-record flood peaks as in 1960 and 1984 and South African-record flood peaks as in 1960 and 1988 are plotted together with neighbouring K=constant lines. The world-record flood peaks seem to have stabilised between K=6,0 to 6,5 which indicates that the sample is fairly complete. The envelope of South African-record flood peaks has shifted upwards during the 28 years in question from about K=5,2 to K=5,6, not least because of increased sample that included inputs from the last century.

Delimitation of maximum flood-peak regions

The compilation of the updated South African data base was completed in 1988. It contained 374 flood peaks observed since 1856, and was supplemented by 145 flood peaks observed in six neighbouring countries in order to facilitate a realistic delimitation of regions across the borders.

In determining the boundaries of homogeneous maximum flood-peak regions the greatest weight was given to the individual K values. Besides the maximum recorded 3-day rainfall, the topography, soil permeability, main drainage network and catchment orientation with respect to dominant storm generating weather systems were taken into account. The result is shown in Figure 6, wherein K=constant regions are delimited. It is seen that the relatively highest floods occur in the eastern-south-eastern coastal belt and adjoining escarpment (K=5,2 to 5,6), characterised by very high storm rainfall and hilly to mountainous relief. The high flood potential decreases from east to west where the climate is arid to desert-like and the relief is flat to undulating.

Regional maximum flood-peak envelopes

These were drawn for each region by plotting the flood-peak data against respective catchment areas, defining the separation between flood zone and transition zone and determining the discharge associated with the envelope value of the maximum recorded 15-minute duration storm rainfall over 1 km^2. Figure 7 shows the plotted data and the envelope curve in region K=4,6 together with its equations in the flood and transitional zones.

The regional envelope lines represent the regional maximum flood peak (RMF) which is thus an empirically established upper limit of flood peaks that can be reasonably expected at a given site. The RMF can be instantly calculated if the geographic position and the catchment area of the site are known.

The most reliable RMF estimates can be expected in catchments of 200 km^2. Beyond this range the particular features of smaller and larger catchments cannot be easily expressed by one common regional coefficient.

Table 4. Comparison of K and K_{pmf}

Number of dams	$K_{regions}$	K_{pmf}
1	4,0	5,34
17	4,6	5,51
41	5,0	5,47
8	5,2	5,60
6	5,4	5,39
2	5,6	5,90

Comparison of PMF and RMF

The comparison of these flood peaks is made difficult because of two circumstances: firstly, PMF and RMF are different concepts (the first is a theoretically derived upper limit obtained by assuming the most severe combination of critical meteorologic and hydrologic conditions, whereas the second is an envelope of observed flood peaks); secondly, there is no objective way to decide on the accuracy of *maximum maximorum* type flood peaks, and the absence of failure is no criterion of quality for a particular method. It then follows that the sole purpose of a numerical comparison is restricted to discovering inconsistencies.

A comparison made of 75 large dams revealed that the mean ratio PMF/RMF was 1,82 with a minimum of 0,54 and a maximum of 4,90. The inconsistency of PMF estimates is manifest in the following table where the regional K-envelope values are compared with the averages of the K equivalents of PMF estimates (K_{pmf}) in six regions.

It is noted in the table that K_{pmf} does not increase progressively from region 4,6 where the extreme flood potential is moderate (central inland areas) to region 5,4 where extremely high peaks are fairly frequent (southeastern and eastern coastal belt). The consequence of this inconsistency is that the error in the PMF estimate can be of the same order as that in the RMF.

Conclusion

The advantages of using the RMF over the PMF are its simple calculation, consistency, and its sounder logical basis for application in conditions where over-conservatism can have significant adverse consequences on the welfare of the community that the project is to serve. Another of its advantages is that approximate values of flood peaks in the 50-year to 200-year recurrence interval range can be quickly determined from the RMF.

Owing to these advantages the use of the RMF has become an accepted method for estimating maximum design floods at large dams in South Africa. In 1991 the RMF method was recommended by SANCOLD as the preferred method in establishing generalised criteria for selecting floods for dam design and safety evaluation.

As is the case with empirical methods, their ability to provide sound estimates depends on the representativeness of the data base. If in future the regional K envelopes are consistently exceeded by more than K=0,1 (7% to 15% increase in discharge), the envelope values and regional boundaries should be revised.

It is appropriate to remember that the estimation of *maximum maximorum* type floods is not an aim in itself. These serve only as a basis for deciding on the maximum design flood for a dam or project. Being so, it is better to use a lower basis which is supported by measurements than to rely on a higher basis derived from a number of unverifiable assumptions.

REFERENCES

Alexander WJR (1990a). *Flood hydrology for Southern Africa.* SANCOLD. Pretoria

Alexander WJR (1990b). *Determination of the design flood for dams.* Proc of the Symposium on Dam Safety. South African Institute for Civil Engineers. Pretoria

Alexander WJR (1993). *Flood risk reduction measures.* Department of Civil Engineering, University of Pretoria. Pretoria

Alexander WJR and Van Heerden J (1991a). *The destruction of bridges by floods during the past 120 years — what went wrong?* Proc of the Annual Transportation Convention. Pretoria

Alexander WJR and Van Heerden J (1991b). *Determination of the risk of widespread interruption of communications due to floods.* Department of Transport Research Report No RDAC 90/16. Pretoria

Du Plessis DB, Dunsmore SJ, Burger CE and Randall LA (1989). *Documentation of the February-March floods in the Orange River basin.* Department of Water Affairs Technical Report TR 142. Pretoria

Estie KE (1981). *The flood disaster of 25 January 1981.* Weather Bureau Newsletter, February 1981. Pretoria

Francou J and Rodier JA (1967). *Essai de classification des crues maximales.* (Essay on the classification of maximal floods). Proc of the IAHS Symposium on Floods. Leningrad

Justin JD, Creager WP and Hinds J (1945). *Engineering for dams.* New York, John Wiley

Kovacs ZP (1982). *Documentation of the January 1981 floods in the South-West Cape.* Department of Water Affairs Technical Report TR 116. Pretoria

Kovacs ZP (1983). *Problems in the estimation of maximum flood peaks.* Proc of the South African National Hydrological Symposium. Pretoria

Kovacs ZP (1988). *Regional maximum flood peaks in Southern Africa.* Department of Water Affairs Technical Report TR 137. Pretoria

Kovacs ZP, Du Plessis DB, Bracher PR, Dunn P and Mallory GCL (1985). *Documentation of the 1984 Demoina floods.* Department of Water Affairs Technical Report TR 122. Pretoria

Lewis AD (1918) *Maximum flood curves.* Department of Irrigation Professional Paper No 1. Pretoria

Midgley DC, Pullen RA and Pitman WV (1960). *Design flood determination in South Africa.* University of the Witwatersrand HRU Report No 4/69. Johannesburg

Reed DW and Field EK (1992). *Reservoir flood estimation: another look.* Institute of Hydrology Report No 114. Wallingford, UK

Rodier JA and Roche M (1984). *World catalogue of maximum observed floods.* IAHS Publication No 143. Wallingford, UK

South African National Committee on Large Dams (1991). *Guidelines on safety in relation to floods.* SANCOLD Safety evaluation of dams Report No 4.

Taljaard JJ (1985). *Cut-off lows in the Southern African region.* South African Weather Bureau Technical Paper No 14. Pretoria

Tenant W and Van Heerden J (1993). *The influence of orography and local sea surface temperature anomalies in the development of the 1987 Natal floods.* Accepted for publication in the South African Journal of Science

Triegaardt DO, Terblanche DE, Van Heerden J and Laing MV (1988). *The Natal floods of 1987.* South African Weather Bureau Technical Paper No 19. Pretoria

Triegaardt DO, Van Heerden J and Steyn PC (1991). *Anomalous precipitation and floods during February 1988.* South African Weather Bureau Technical Publication No 23. Pretoria

Van Bladeren D and Burger CE (1989). *Documentation of the September 1987 Natal floods.* Department of Water Affairs Technical Report TR 139. Pretoria

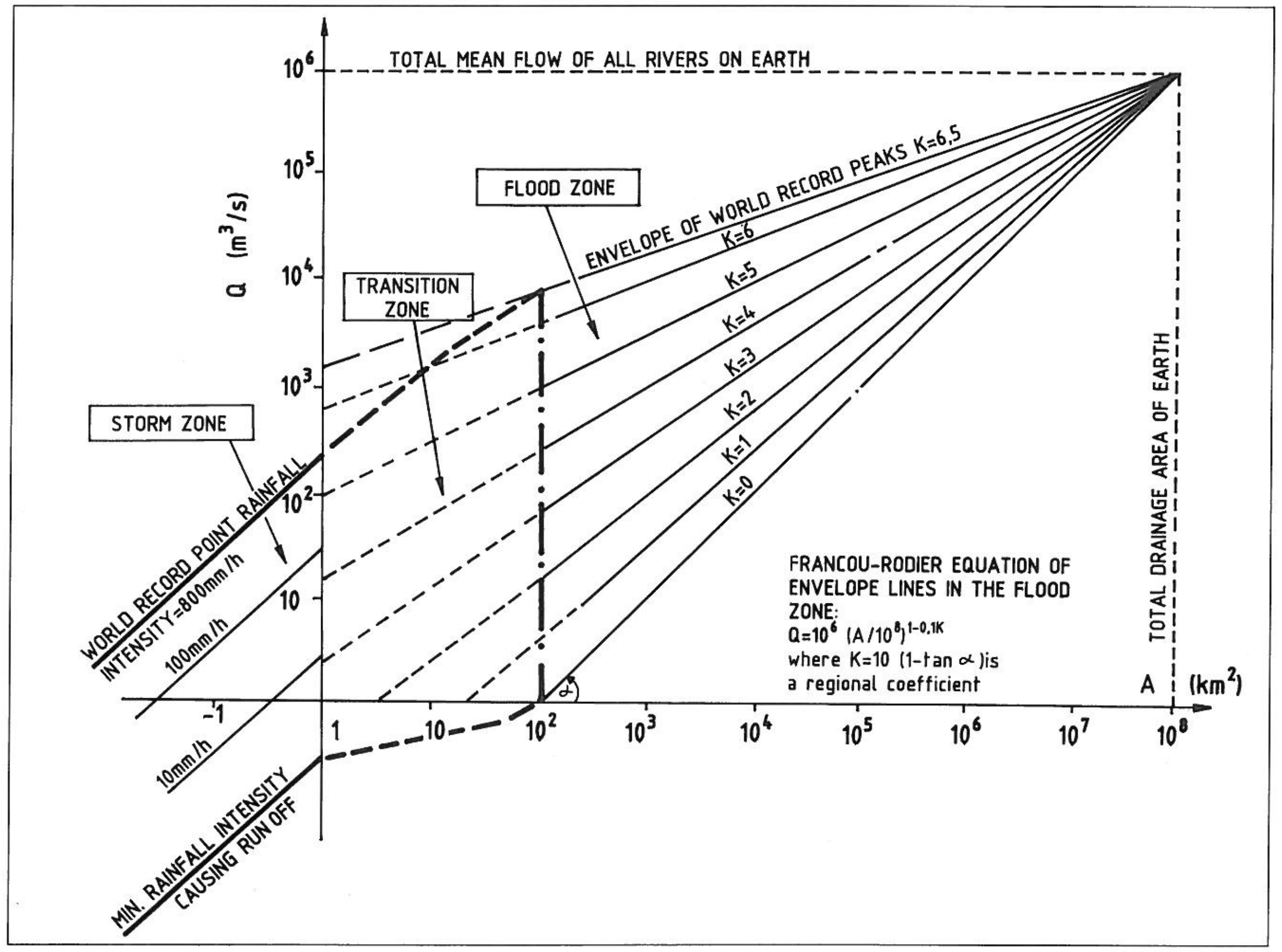


Figure 4: The Francou-Rodier diagram of regional maximum flood-peak classification

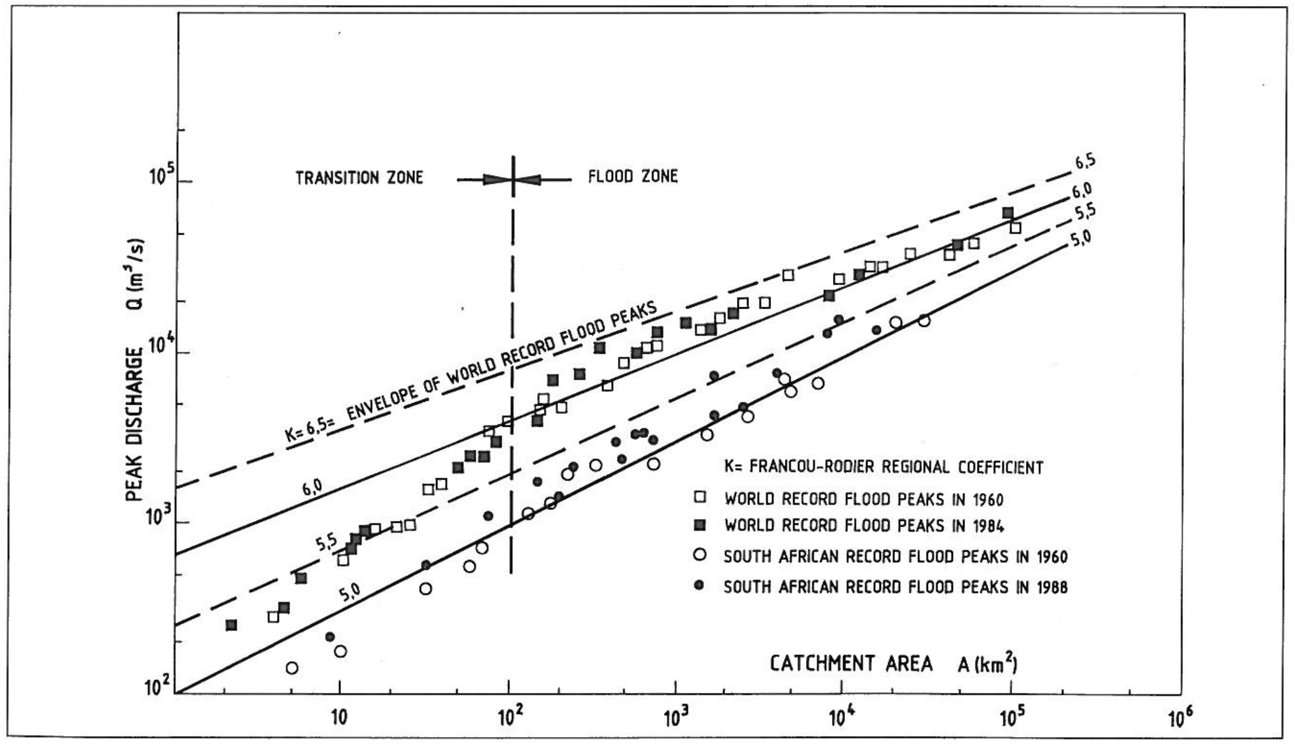


Figure 5: World and South African record flood peaks

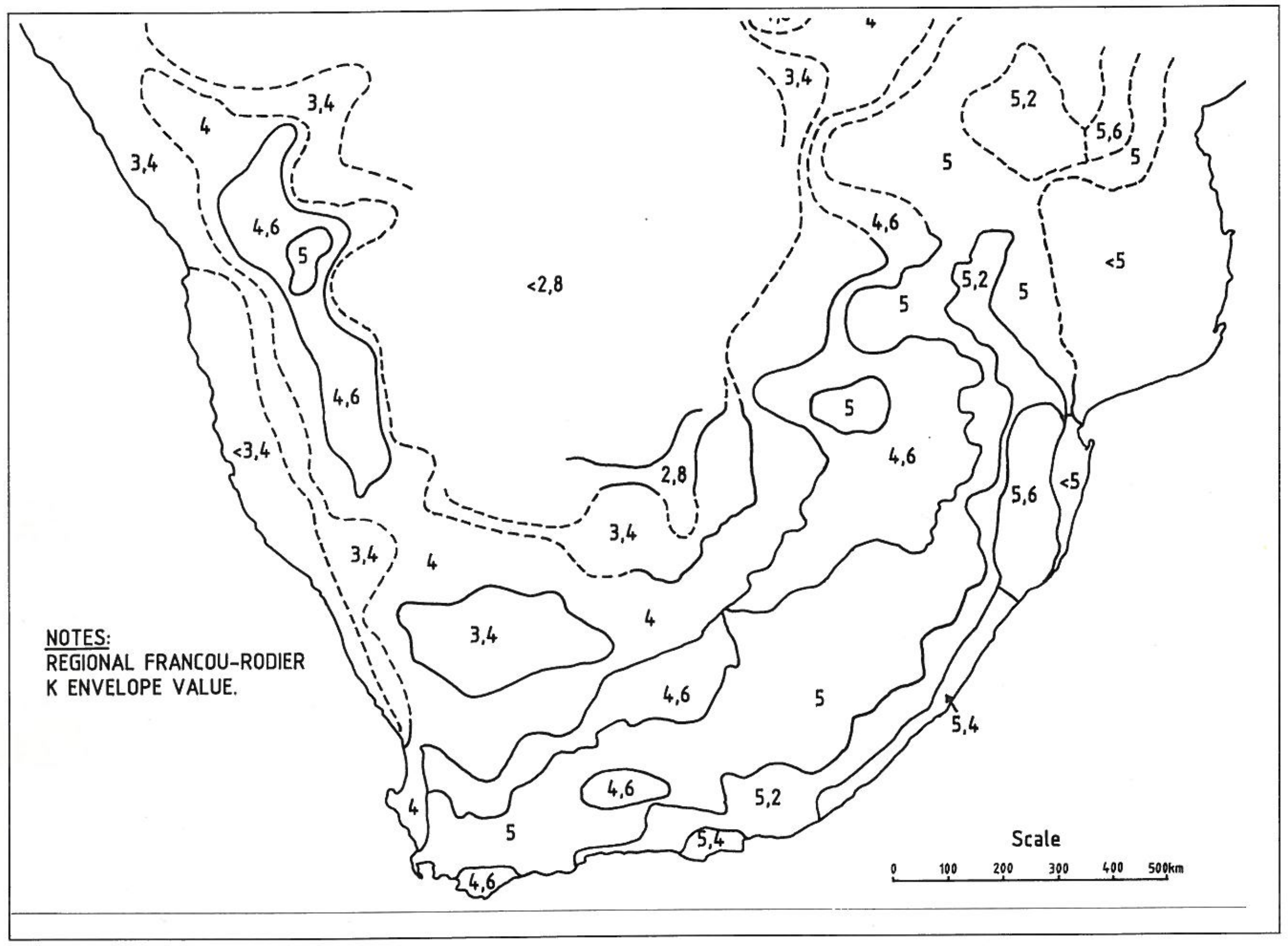


Figure 6: Maximum flood-peak regions in southern Africa

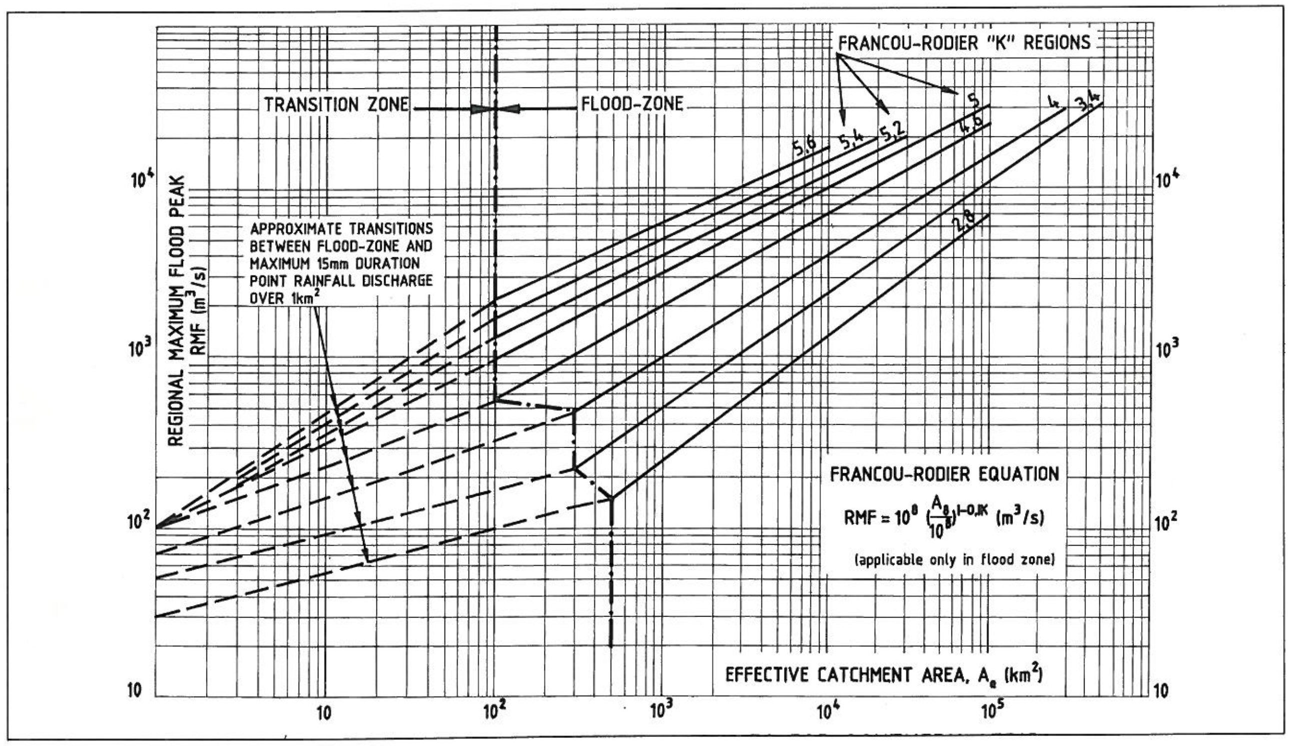


Figure 7: Regional maximum flood-peak curves for southern Africa

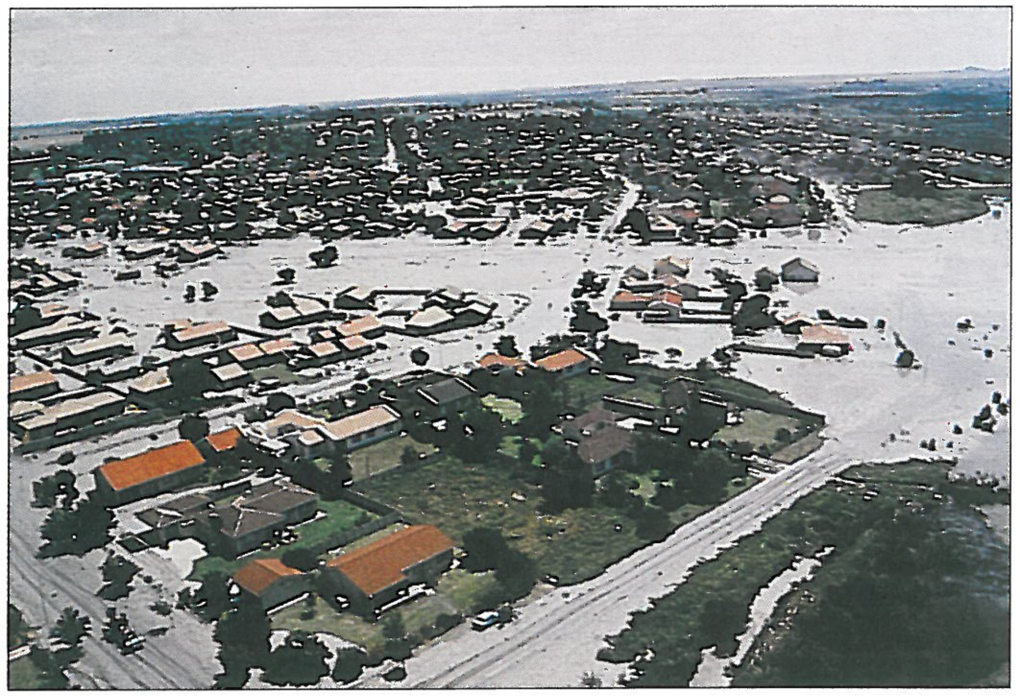
FLOODS AND THEIR EFFECTS AT SOME DAMS

Albert Falls Dam during the September 1987 flood with the washed away railway bridge downstream of dam (Mgeni River)

Spitskop Dam, breached due to overtopping by the February 1988 flood, with side-channel spillway on the right (Harts River)

Douglas Weir (labyrinth design) completely drowned out during the February 1988 flood and barely visible, but survived (Vaal River).

Inanda Dam during construction (September 1987) partially inundated by a severe flood (Mgeni River)

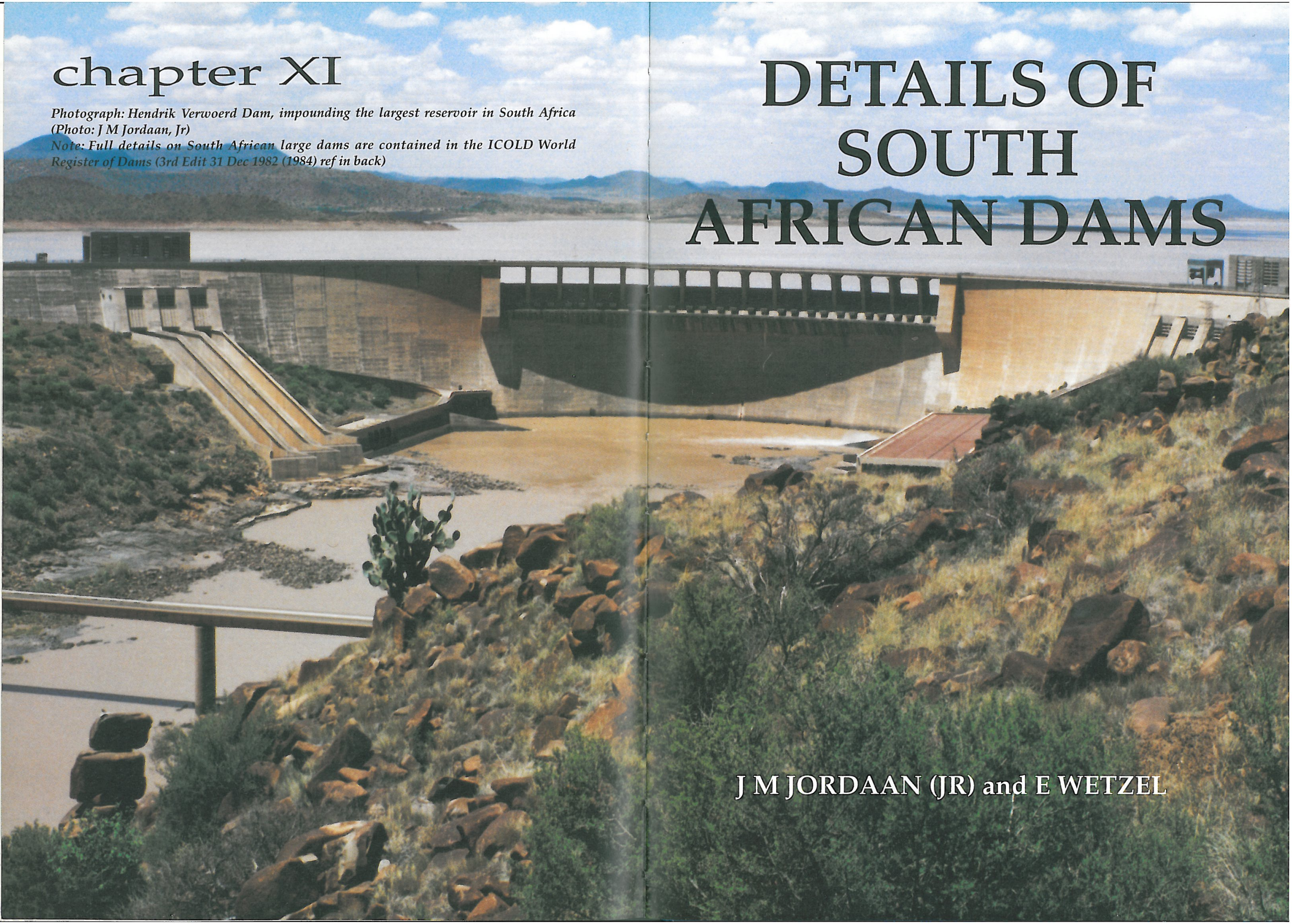


An example of the results of a slimes dam failure — Merriespruit, Virginia, OFS

Harmony Gold Mine tailings dam failure (February 1994) and flooded town of Merriespruit, Virginia, OFS

chapter XI

Photograph: Hendrik Verwoerd Dam, impounding the largest reservoir in South Africa (Photo: J M Jordaan, Jr)
Note: Full details on South African large dams are contained in the ICOLD World Register of Dams (3rd Edit 31 Dec 1982 (1984) ref in back)



DETAILS OF SOUTH AFRICAN DAMS

J M JORDAAN (JR) and E WETZEL

DETAILS OF SOME SOUTH AFRICAN DAMS

by J M Jordaan Jr, E S Wetzel and L Ruzicka

"When we build, let us think that we build for ever. Let it not be for present delight, nor for present use alone; let it be such work as our descendants will thank us for." — John Ruskin

This quotation certainly rings true for South Africa's large dams, for while they may not be spectacular by world standards in terms of size or number, they nevertheless reflect in innovative design the advances of dam-building technology, adapted and developed to uniquely suit the country's specific needs — needs that will still be growing tomorrow, but will, it is hoped, be satisfied by today's planning.

INTRODUCTION

South Africa cannot claim such ancient waterworks as Roman aqueducts, her large dams being of recent vintage (post 1912). One of the oldest large dams is the Vaal Barrage near Vereeniging, built in 1923. During the early part of this century (1915 to 1935) quite a few large dams (higher than 15 m above lowest foundation) were built all over South Africa, mainly as a work-providing scheme after the First World War.

Early dams

Some of the landmark dams built in the early part of this century in South Africa are the Hartbeespoort Dam (59 m) near Pretoria, built in 1923, Lake Mentz (34 m), Kammanassie (41 m), Grassridge (24 m), Lake Arthur (38 m) and Van Ryneveldspas, the latter five all in the Cape Province. These were the first golden years of dam building in South Africa.

The current status

Since these early days, dam building in South Africa has gone from strength to strength. The country has 485 large dams at present — built by either the Government, local authorities or private owners. The outstanding innovations and trend-setting designs mainly evolved after World War II, proving South African engineers to be dam builders *par excellence,* receiving awards and recognition for their work locally as well as worldwide. *"In Southern Africa some of the most modern dams in the world have been, and still are being constructed" — BJ Vorster* (Olivier 1977).

Since the 1970s, the South African Institution of Civil Engineers (SAICE) has presented its prestigious annual award for the most outstanding civil engineering project no less than seven times to the Department of Water Affairs for some of its ingenious water projects.

This chapter deals with examples of some of these unique structures created to impound, control and conserve water in South Africa.

INNOVATIONS

The major advances in the creation of storage structures can primarily be classified as structural, hydraulic and material, and some of the developments and innovations are dealt with in sequence below.

Structural

Engineering geology is probably one of the most important disciplines when it comes to the design and construction of a new dam. The selection of a suitable dam site influences the styles of design and flood-handling capabilities — therefore close association between the engineering geologist, the structural and the hydraulic engineer is important. The Inanda Dam serves as a good example, where the particular design layout of a composite earth and concrete dam was dictated by the foundation geology.

The wide variety of dams in South Africa, ranging from the largest earth dam (Sterkfontein, 93 m high), to the highest arch-gravity concrete dam (PK le Roux, 107 m high), and from rockfill dams (Rockview, in the Palmiet Pumped Storage Scheme), to the sophistication of multiple-dome (Wagendrift) and double-curvature arch dams (Pongolapoort) underlines the overriding influence of a variable geology on the most economical solution for damming a river.

The whole spectrum of construction techniques in earth, rock and concrete can, in fact, be found among the country's dams from single-zone earth (Vaal Dam) to dressed-stone masonry (Bulshoek), from conventional gravity concrete (Allemanskraal), prepacked concrete (Erfenis) to multiple-arch (Beervlei), and from bulb-head buttress (Doorndraai), through double-curvature arch (Hendrik Verwoerd) to arch-gravity roller-compacted concrete (Wolwedans) dams. Some of the thin-shelled arches even match their European counterparts in their slenderness (Roode Elsberg and Craigie Burn).

The ***prepacked*** and ***roller-compacted concrete*** methods justify a more detailed description, since they changed dam-building techniques and South Africa was at the spearhead of the development of both these methods.

The *prepacked* method was first used during the construction of the Erfenis Dam in the Orange Free State in 1959. Boxes to be concreted were first packed with stone of various sizes and a cement mortar was then pumped in to intrude into and fill the voids and turn the contents of the box into one solid block of concrete. This method was necessary as the local sand was so fine that it was unsuitable for good concrete, and coarse sand would have had to be imported over a long distance. The local fine sand was however suitable for the cement mortar intrusion process.

Roller-compacted concrete (RCC) is a more cost- and time-effective dam construction material than conventional mass concrete. It can be described as a zero-slump concrete, which is spread in layers by a bulldozer and compacted by a vibratory roller. Less shrinkage takes place in RCC, and it can therefore be placed in continuous lengths, rather than in single units, as is the case with mass concrete. Because it contains less cementitious material, it is also less susceptable to the cracking caused by the volume change due to heat of the chemical reaction that takes place when cement sets, followed by cooling and shrinking.

The De Mistkraal diversion weir in the Eastern Cape, which forms part of the greater Orange River Project, was the first dam in South Africa to be constructed mainly in RCC and was completed in 1986. Zaaihoek Dam, completed in 1987, ranks as the first dam where full-scale implementation of RCC was introduced in South Africa, while the Knellpoort Dam, completed in 1988, is the first arch-gravity dam in the world to be built by using the RCC construction method. Wolwedans Dam, an arch-gravity dam of impressive proportions, was built in RCC.

Some of the main developments in the structural category are as seen in finite-element analysis, double-curvature multiple arch dams, the advance of RCC; and the design of composite earth and concrete gravity dams, such as the Inanda Dam in Natal, completed in 1989.

Hydraulics and hydrology

In the hydraulics field, including also hydrological considerations, the innovation making the latest major impact on design was the adoption of *regional maximum flood design* criteria. This is now preferred to the more conventional *standard frequency flood* and *probable maximum flood* concepts, which are largely outdated in current South African practice, as described more fully in Chapter IV, last section.

This also has had a major influence on dam safety considerations, inasmuch as the flood-handling capabilities of many large dams had to be re-evaluated, and in certain cases their spillways had to be enlarged, as was done for Morgenstond Dam. The other option is to design new dams with ample flood handling capabilities in the first place, with breaching sections, and with both uncontrolled and controlled spillways. This was done for the Grootdraai Dam near Standerton, the earth embankment of which incorporates a fuse plug that will breach during extreme flood conditions to prevent overtopping and subsequent damage to the earth embankment.

Another decision was to obviate crest gates in late vintage dams where operation and maintenance could be a problem. On the other hand, older dams that are still solely equipped with crest gate flood-handling facilities, necessitated the introduction of a network of flood-warning stations, e.g. in the Vaal catchment.

The Department erected a network of telemetry stations at selected points in the catchment area. These stations are equipped to transmit rainfall and flood observations by radio to a master station at the Vaal Dam. With the inflow into the dam forecast, the behaviour of the flood water in the dam was simulated with the aid of a computer, and it is now possible to optimise operating procedures concerning the opening and closure of gates during floods. In so doing the potential damage downstream of the dam is reduced and the safety of the dam is ensured. Further developments in flood-warning systems involve the use of meteor-burst and satellite communications to relay flood data to operation centres. These can be regarded as major advances.

Dealing with the hydraulics of flood control and energy dissipation, forms part of the final hydraulic design process. The types and forms of energy dissipation structures are numerous, ranging for example from the conventional flip bucket at the Pongolapoort Dam to the hydraulic-jump stilling basin at the Nooitgedacht Dam.

Various crest splitter dissipation devices were designed: the *Roberts splitter* was first used at the original Loskop Dam on the downstream face of the wall to dissipate the kinetic energy of the overflowing water. The idea of a splitter was developed in the 1930s by Lt-Col DF Roberts, the resident engineer at the Department's very first hydraulics laboratory near the dam site. It was later also used at the Nagle and Hendrik Verwoerd Dams, and many others, while stepped downstream spillway slopes were incorporated at the Clanwilliam and Zaaihoek Dams, among others.

High energy dissipating outlets are found at the Sterkfontein Dam and at most dams that are equipped with hollow jet-disperser valves such as the Katrivier Dam. Other types of spillways on South African dams also include the "morning glory" (at the Ebenezer Dam) and syphon spillways (at the Mockes

Dam). A jet-flow gate is installed at the Hazelmere Dam.

Mechanical flood-control gates of high sophistication, such as remote-controlled radial gates, were constructed at the Driel Barrage, the main diversion unit of the first phase of the Tugela-Vaal Project; while *fish-belly flaps* were incorporated at the Vaalharts Weir. All the above bear testimony to the achievements of mechanical and electrical engineers towards dam building. Some of the more static solutions to flood-handling capabilities are labyrinth weirs (at the Douglas Dam) and sacrificial breaching sections (at the Morgenstond Dam).

Novel handling of floods via bypassing channels is found in the Nagle Dam, where a flood diversion structure was provided at the upstream extremity of the dam site, with the diversion channel cutting through the intervening divide. Heavily silt-laden waters can thus be bypassed downstream and the reservoir can be filled on the recession part of the hydrograph.

The sediment problem led to hydraulic silt mitigation structures such as the low-level drawoff or curtain-walled portion of the spillway at Nooitgedacht Dam and the off-channel pumping and storage project (Tienfontein pump station to Knellpoort Dam). At the Nooitgedacht Dam, a unique structure has been incorporated in the central section of the dam, intended to counteract silting of the basin by discharging silt-laden density currents instead of clearer stored water over the spillway during times of flood. This will increase the period before silt accumulation in the dam basin would necessitate the raising of the dam wall.

One large dam, the Welbedacht Barrage in the Orange Free State, the main water artery of the province's capital, Bloemfontein, is equipped with five of the largest radial gates in the country. Unfortunately, it is already 85 per cent sedimented, because lack of catchment monitoring precluded efficient use of the gates. Its lost capacity has been replaced by the reservoir of Knellpoort Dam, an off-channel storage facility purposefully created since. The Vaal Dam was raised twice, the second time replacing the 60 vertical lift gates with higher gates. The Bloemhof Dam, with 20 gates, as well as the Albasini and Doorndraai Dams are equipped with radial gates for flood release purposes.

A hydraulic achievement unique to South Africa was the Grootdraai Dam Emergency Augmentation Scheme, when the flow of the Vaal River was reversed over a reach of 100 km with the purpose of augmenting the water supply to the Grootdraai Dam on the Eastern Transvaal Highveld, which supplies water for the national power grid. The scheme involved the construction of seven dams and emergency pump stations in a record-breaking period of six months. This scheme was later awarded the South African Institution of Civil Engineers' award for the most outstanding civil engineering achievement of 1983. Other emergency water supply schemes, not involving new dams, were also resorted to, sometimes modifying existing dams.

Materials and construction techniques

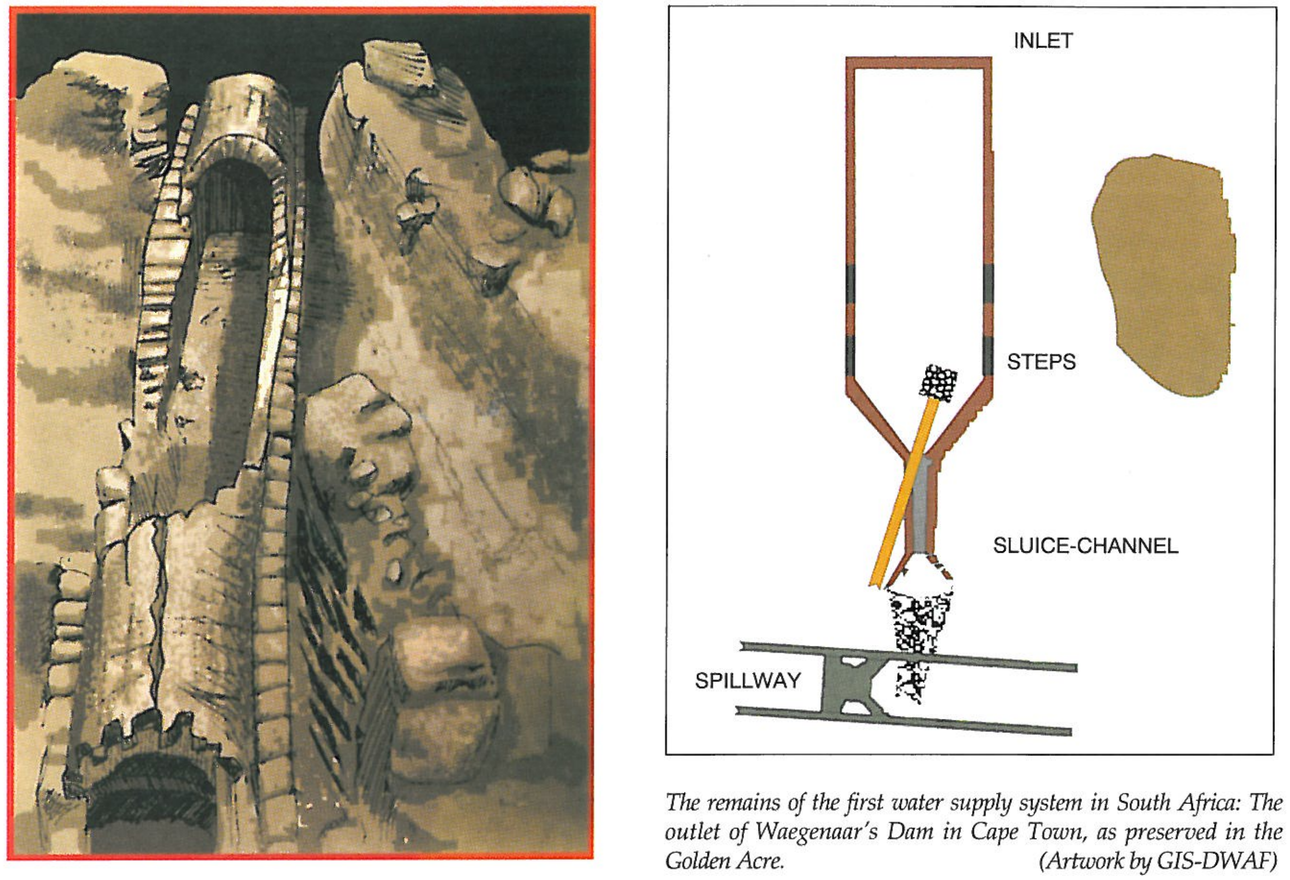
Materials, specifically cementitious materials, of an innovative nature are found in South African dams, e.g. the use of sulphate-resistant cement (Beervlei Dam), and colloidal concrete mortar (Erfenis Dam). Blast furnace slag and pulverised fuel ash have been used as cement-extenders in most concrete dams since 1970. Slag was used for the first time in dam construction by the Department of Water Affairs during the construction of the Roodeplaat Dam in the late 1950s. The use of cement extenders enables the quantity of ordinary Portland cement in concrete to be reduced, thereby reducing the heat produced by the chemical reaction of cement hydration and setting.

The pre-cooling of aggregate and mixes and the addition of ice to reduce thermal expansion were first applied in South Africa at the Pongolapoort Dam. At the Gamkapoort Dam in the Cape Province an air entrainer had to be incorporated to improve the workability of the concrete. This dam is one of the first where this method was applied in South Africa.

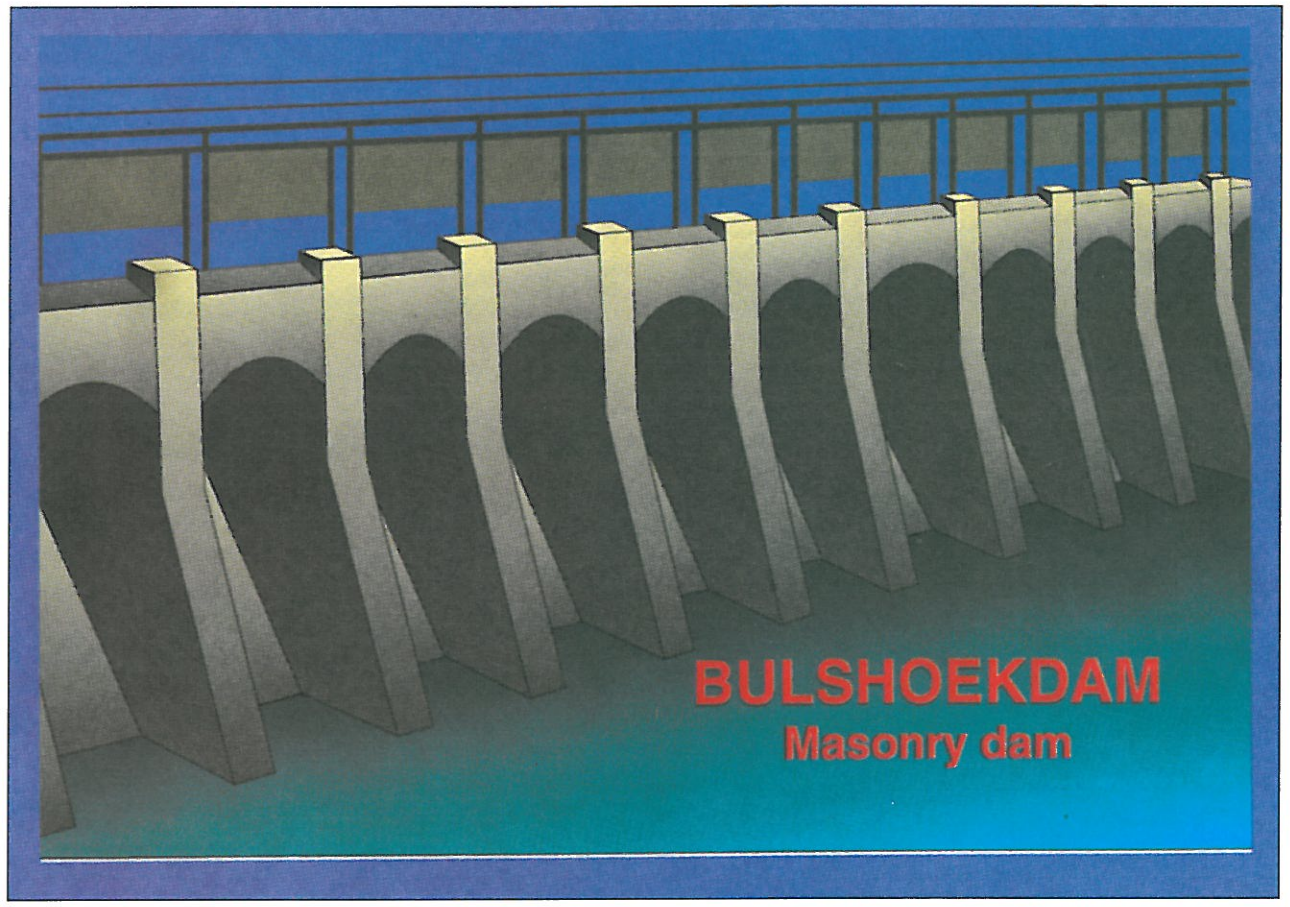
Some less ideal dam sites required that better than existing dam design and building techniques had to be developed. An example of a dam where alternative building techniques were used due to the unfavourable geological formations at the dam site is the Paul Sauer Dam, the first large cupola-type dam constructed in South Africa. As the quality of the foundation material was not very good, extensive measures were required to safeguard the dam structure and its foundations. It included, *inter alia*, grouting under the spillway apron and cable stressing the right flank abutment.

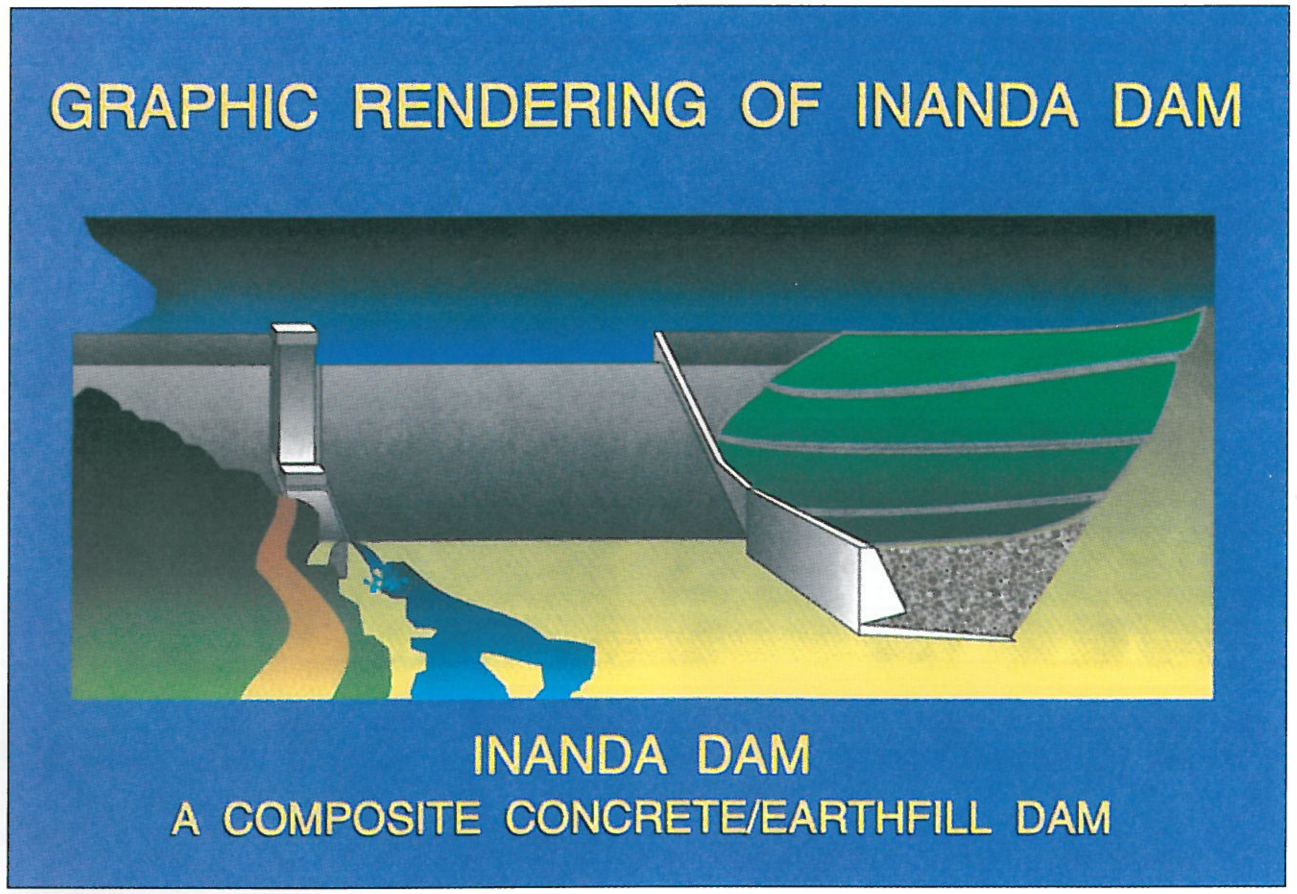
UNUSUAL PLANNING, DESIGN AND CONSTRUCTION DEVELOPMENTS, AND BI-NATIONAL PROJECTS

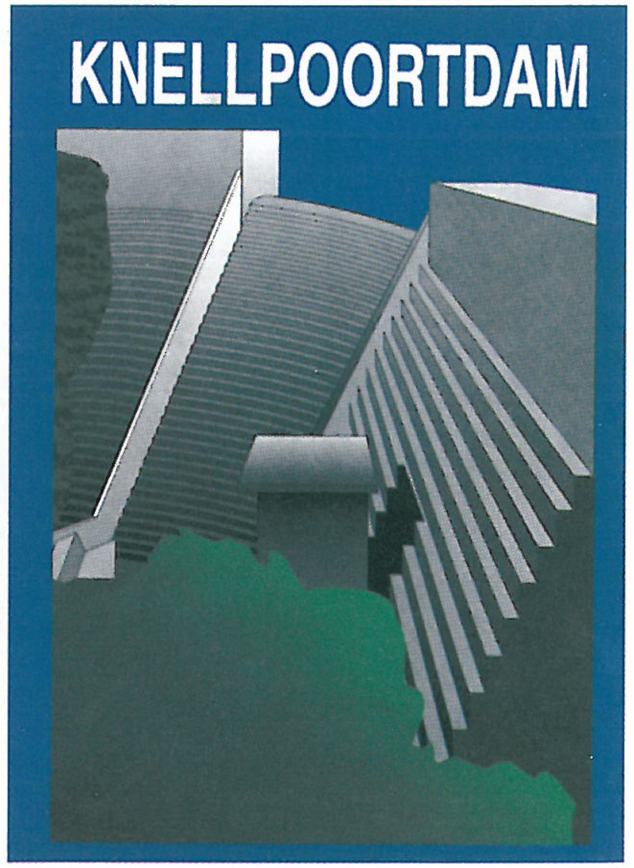
Much of the more innovative dam-building technology has evolved largely as a result of the need for the extension of the water supply of the country through trans-watershed diversions, the need to reduce evaporation losses, and to conserve reservoir capacity against losses through the sedimentation enemy. Of the former, the trans-Drakensberg diversion from



The remains of the first water supply system in South Africa: The outlet of Waegenaar's Dam in Cape Town, as preserved in the Golden Acre. *(Artwork by GIS-DWAF)*







Natal into Transvaal (the Tugela Vaal Project) gave rise to the Drakensberg Pumped Storage Scheme with its unique Driekloof Dam with reversible-flow spillway. Other multipurpose projects such as the Jonkershoek and the Palmiet water-transfer schemes; the Rockview Dam pump-storage pond; the Kogelberg arch-gravity dam (the former's low level complement) and dam-tunnel links, involving reversible flow hydraulics, such as the Theewaterskloof Dam and Charmaine Tunnel, followed.

Dams in the neighbouring countries had, and still have, an important bearing on South African present and future water technology and economy, mainly relating to potential international multipurpose projects. Joint projects such as the Cahora Bassa (Mozambique — South Africa), the Lesotho Highlands Water Project (Lesotho — South Africa), and Driekoppies Dam are bi-national and bear witness to the close ties that bind South African dams and their builders to the broader southern African and international scene of large dams and their importance to mankind, Olivier (1975, 1978) and Jordaan (Sr) (1950, 1969).

South African engineers have made significant contributions to the planning of water projects involving major dams in the following instances:

- Building of single to multipurpose dams such as the Hendrik Verwoerd Dam, whose main purposes are water supply/irrigation and power generation.

- River and catchment development, such as the Orange and Mgeni Rivers, where a series of dams were built to satisfy the needs of the users in the specific catchment areas.

- Trans-watershed diversion projects (Tugela-Vaal, Usutu-Vaal, and Riviersonderend-Berg).

- Pumped storage projects such as the Steenbras, the Drakensberg and the Palmiet.

In design aspects excellent development progress was made by creating various types of dams: earth and concrete gravity (Allemanskraal, 1960); multiple-arch (the first was the Churchill, 1940); single or multiple-dome, thick-cylinder arch, arch-gravity, double-curvature (Hendrik Verwoerd, 1971); buttress, face-sealed earth and rockfill dams (Rockview, 1987), and RCC gravity and RCC arch-gravity dams (Knellpoort and Wolwedans). (Arch-gravity dams differ from gravity dams in that the axis is curved, the cross-section is thinner and structural arching is developed to help withstand the water loading.)

Developments in the dam construction field include the use of cement extenders (slag and fly-ash), aggregate precooling with ice, and applications of established methods such as slurry-trench excavation, dispersive clay stabilization, and employing devices involved in bulk-handling and placing of materials e.g. roller-compacted and conventional concrete, such as cableways, split-drum mixers, pneumatic cement silos and also many varieties of earth moving equipment.

NOTABLE LEADING ACHIEVEMENTS IN DAM BUILDING IN THE RSA: LANDMARK DAMS

The following twelve examples of large dams and their systems are chosen to illustrate certain achievements, each one of which can be considered a champion in its own right at the time of its completion. In most cases the dam cannot be considered alone, but rather as the main component in a more complex system, considered a landmark project.

1 Vaal Barrage

The Vaal Barrage, situated about 80 km downstream of the Vaal Dam, is one of the earliest large dams in the country. It was built in 1923, and is the seat of Rand Water's distribution system (originally the Rand Water Board, the first water board to be established in the country, 1903). It was privately constructed and owned, with the main purpose of supplying water to the Pretoria-Witwatersrand-Vereeniging (PWV) region.

The Barrage, a gated concrete-gravity structure, has a gross storage capacity of 56 712 m^3 and a catchment area of 47 118 km^2. It supplies water for domestic and industrial use to an area of more than 16 000 km^2 with a present population of over five million people.

2 Pongolapoort Dam

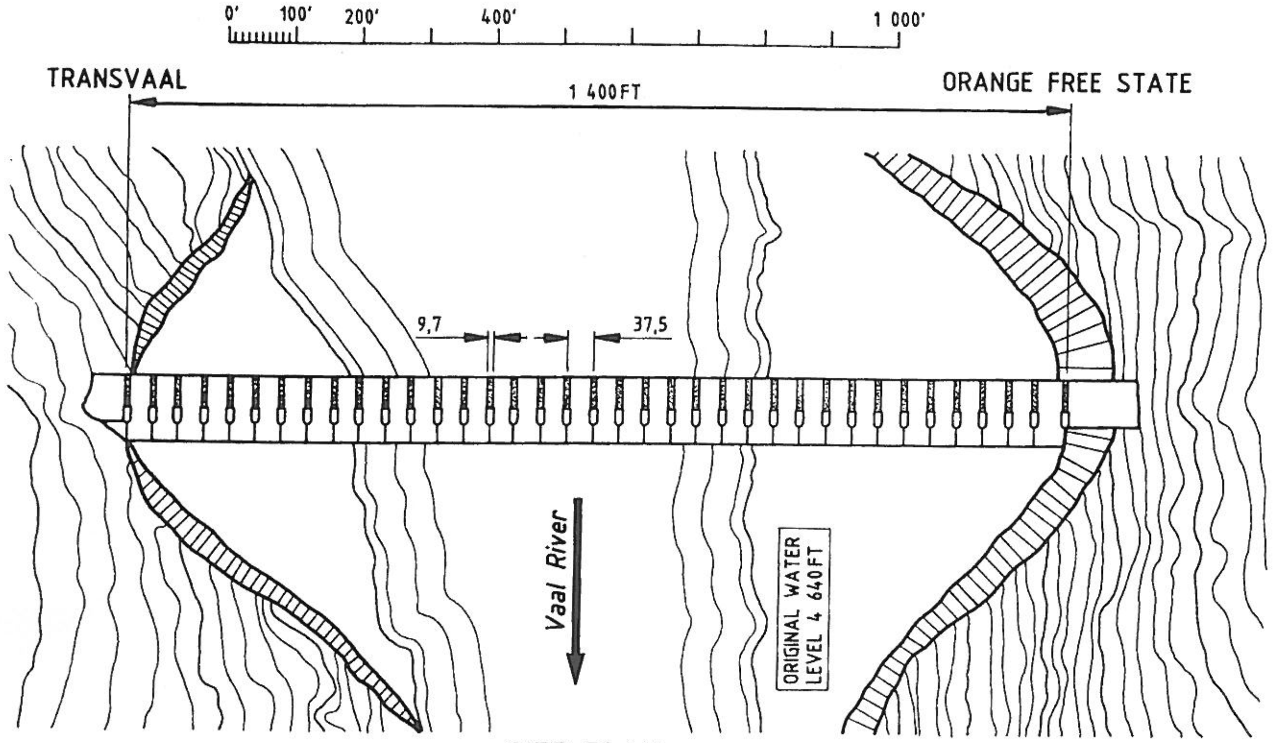
The Pongolapoort Dam on the Phongolo River is the largest dam in KwaZulu-Natal and was completed in 1973. It was the second largest double-curvature single-arch dam and was built mainly for the irrigation of the undeveloped Makatini Flats. Nowadays it is also used for flood control and river regulation in addition to irrigation water supply.

The dam has both a controlled and an uncontrolled spillway. It was the first dam in the country where artificial cooling was provided during construction by precooling of the aggregate and addition of ice.

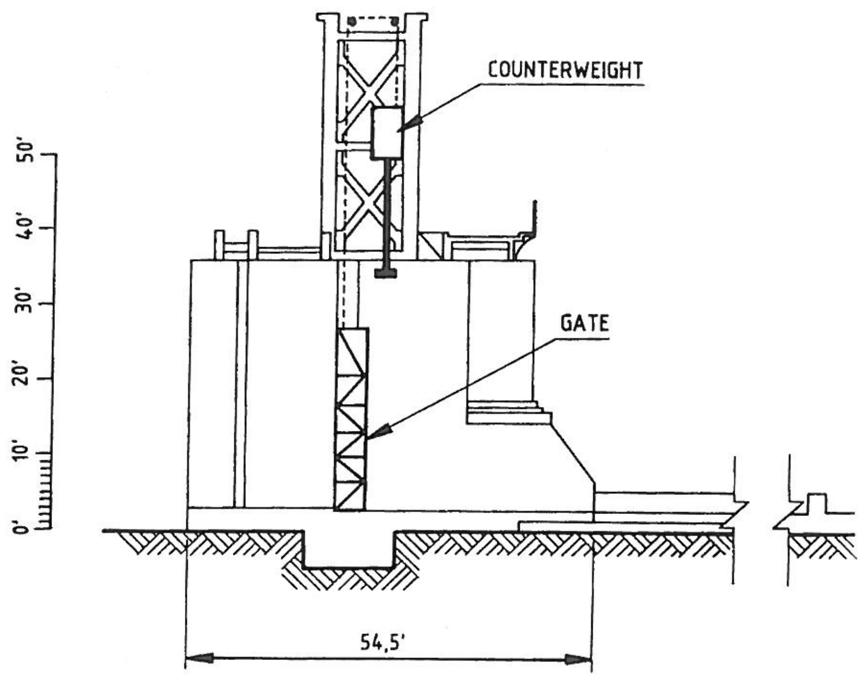
Data — Pongolapoort Dam

Type	Concrete arch
Height above lowest foundation	89 m

Vaal River Barrage

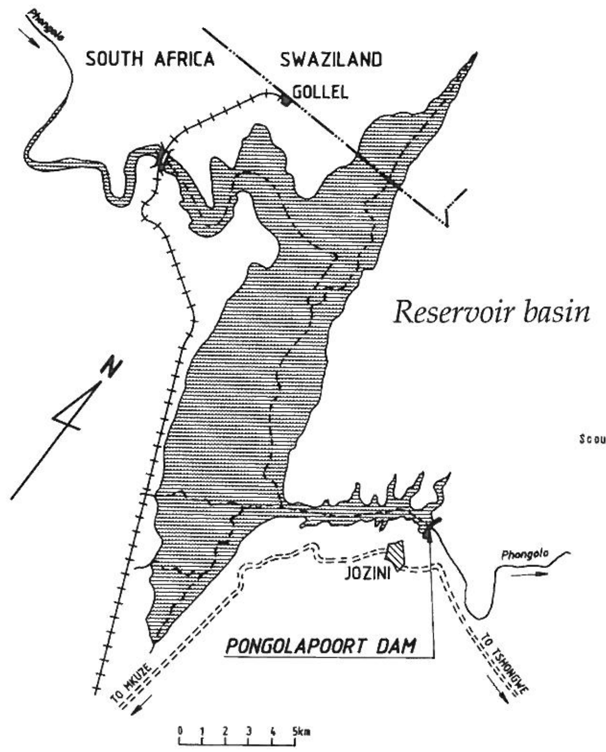


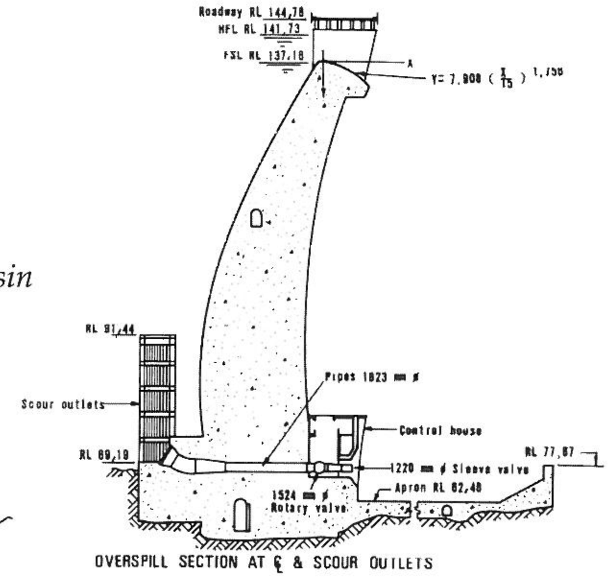
SITE PLAN

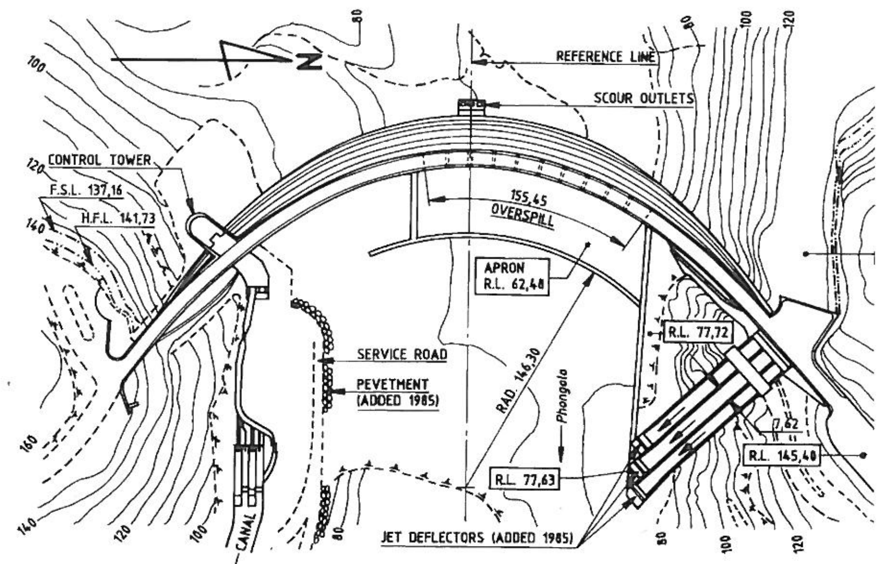


SECTION

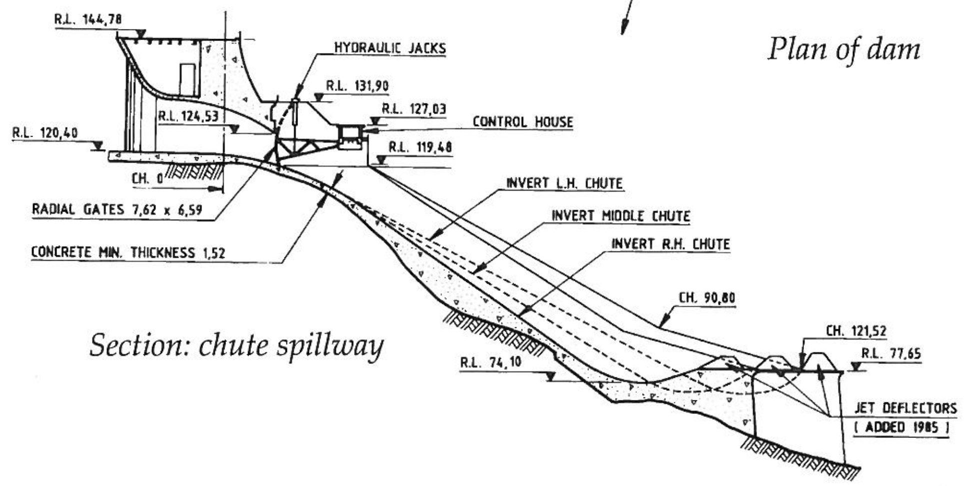
Pongolapoort Dam







Plan of dam



Section: chute spillway

Gross capacity of reservoir	2 500x10^6 m^3
Length of crest	515 m
Volume content of dam	575 000m^3
Type of spillway (3 radial gates with chutes plus free-fall over-spill crest)	Controlled and uncontrolled
Max discharge of spillways	Uncontrolled 2 640 m^3/s Controlled 2010 m^3/s

3 Wemmershoek Dam

Completed in 1957, the Wemmershoek Dam forms part of a scheme comprising the dam, a treatment plant, 50 km prestressed concrete pipeline, a service reservoir and a number of subsidiary pipelines. It was built for the city of Cape Town and local authorities, embracing an area of about 440 km^2. It was privately designed and constructed, and is owned by the Municipality of Cape Town.

The dam is of the earthfill type with pitched rock (rip-rap) protection on both upstream and downstream slopes. It has a lateral spillway controlled by three gates, and discharges flood water by way of a chute to the river bed below. It has a detached intake/outlet tower located upstream of the dam wall.

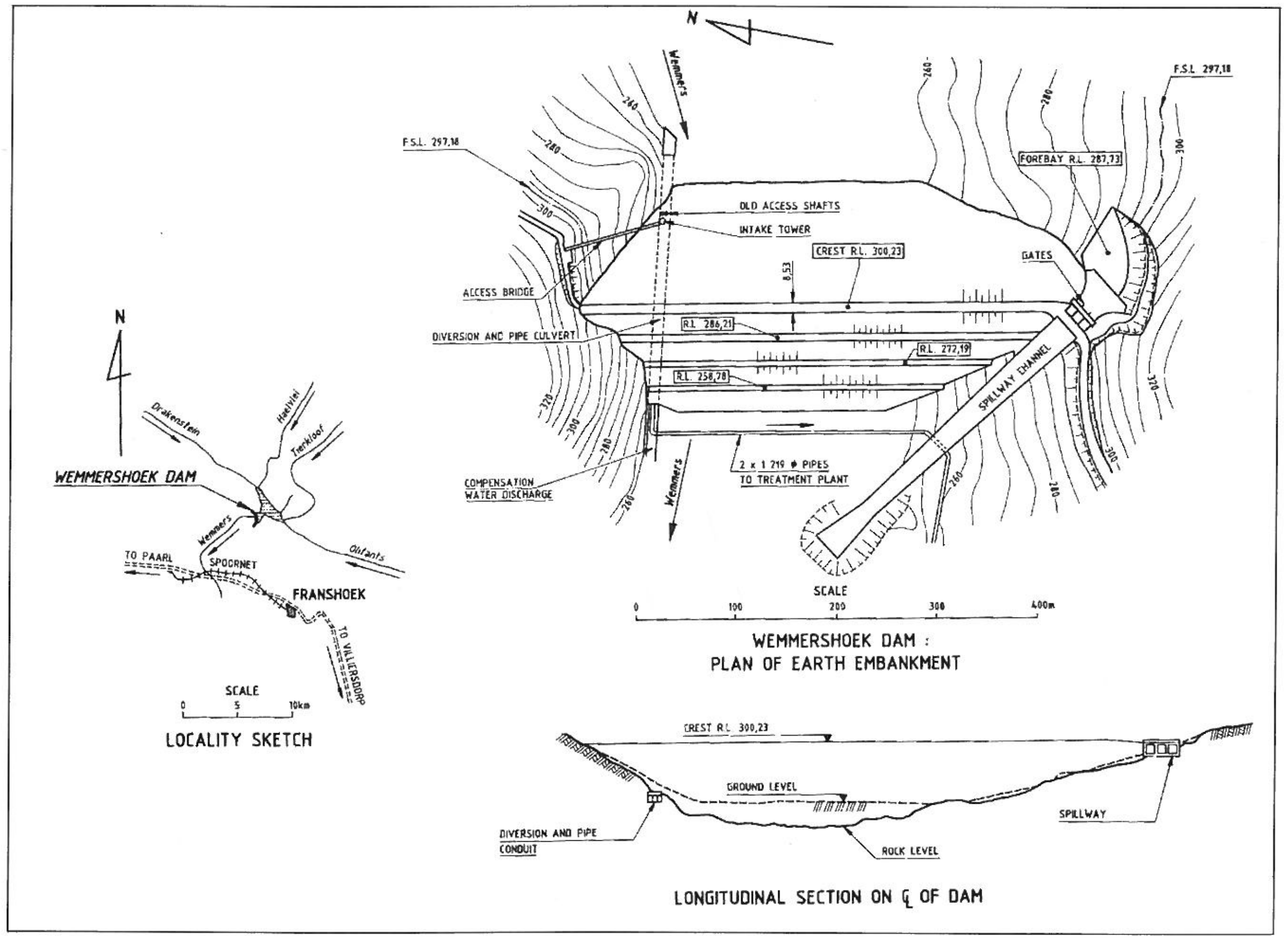
Data — Wemmershoek Dam

Type	Earthfill
Height above lowest foundation	53 m
Gross capacity of reservoir	58x10^6 m^3
Crest length	488 m
Volume content of dam	2 886 000 m^3
Type of spillway	Controlled
Max discharge of spillway (3 radial gates and chute)	1 065 m^3/s

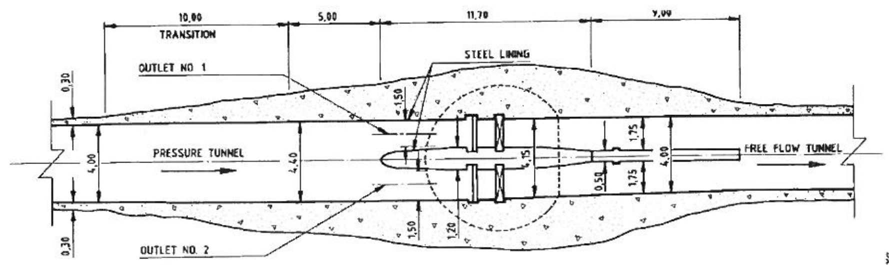
4 Sterkfontein Dam

The Sterkfontein Dam on the Nuwejaarspruit near Harrismith is the largest earth dam in the country (19x10^6 m^3) and was the only dam in the RSA when its first stage was completed in 1977 to qualify for inclusion in the ICOLD *Register of the World's Largest*

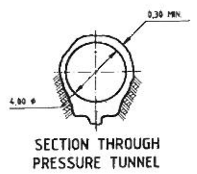
Wemmershoek Dam

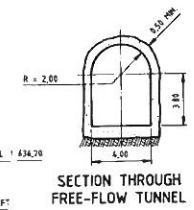


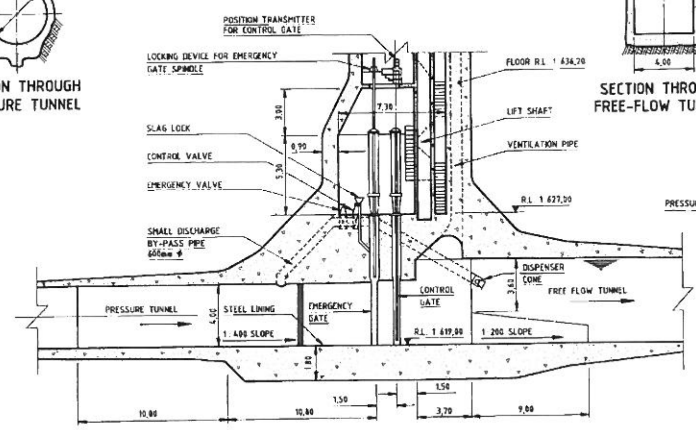
Sterkfontein Dam — Details *(Ref. Figure 4, p 110)*



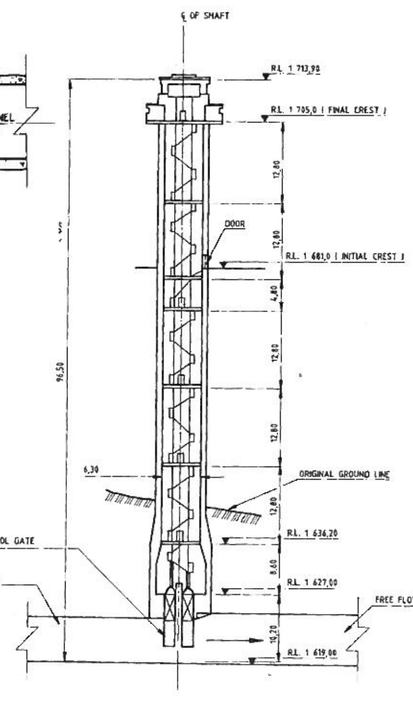
Outlet works plan section



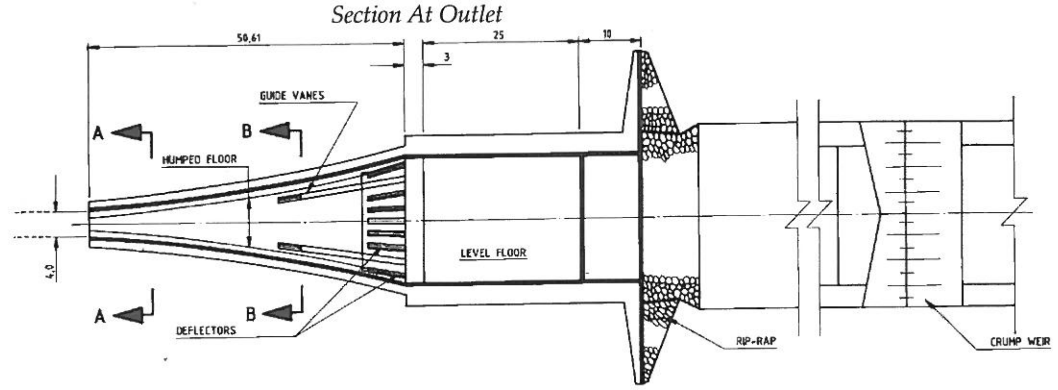




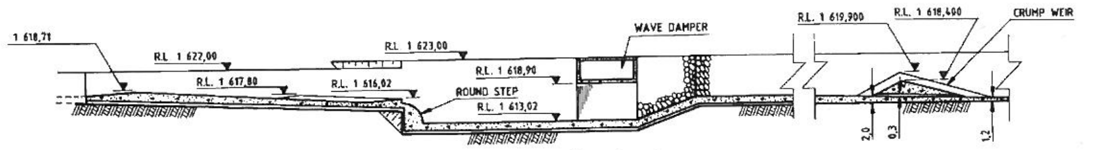
Section At Outlet



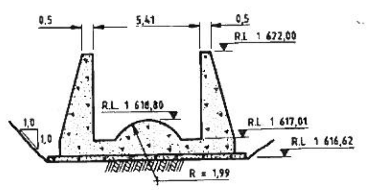
Section through control shaft



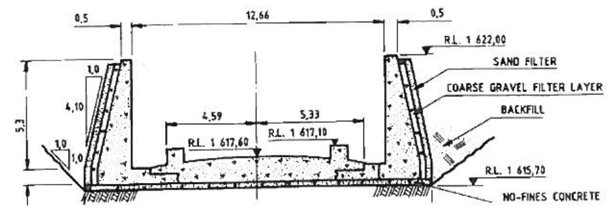
Plan of Stilling Basin



Cross-Section of Stilling Basin



Section A-A



Section B-B

Dams. The dam wall was raised by 24 m in 1983 to 93 m. It is unique because it has no spillway. Sterkfontein is the country's first water-transfer receiving reservoir and forms part of the largest pumped storage power project, namely the Drakensberg Pumped Storage Project. (The Goedertrouw Dam in KwaZulu-Natal is the second highest earth dam : 88 m.)

The Driekloof Dam, forming the upper reservoir of this pumped storage scheme, lies in the arm of the Sterkfontein Reservoir. It will from time to time be subjected to full submergence on both faces as well as rapid drawdown on both sides.

Water from the Tugela River will first fill Driekloof, and the water for interbasin transfer will flow over the spillway into Sterkfontein. Therefore, regardless of the water level of Sterkfontein, there will always be water in Driekloof to operate the generating cycle of the pumped storage hydro-electric power plant.

Data — Sterkfontein Dam

Type	Earthfill
Height above lowest foundation	93 m
Capacity of reservoir	2 656x10^6 m^3
Crest length	3 060 m
Volume content of dam	19 000 000 m^3
Type of spillway	None
Capacity of outlet works (no spillway)	220 m^3/s
Surface area at full supply level	6 937 ha
Catchment area	191 km^2

5 Inanda Dam

The Inanda Dam was built on the Mgeni River in Natal, one of the most reliable rivers in the country. It forms part of Umgeni Water, responsible for supplying potable water to metropolitan areas of Durban-Pietermaritzburg as well as areas of KwaZulu/Natal. This dam is a composite earth and concrete structure. The central mass-gravity concrete section contains the spillway.

The dam wall is designed in such a way that it has two sets of outlets. It is an interesting design in that water of different qualities can be abstracted and released into the river. Because the quality of the water varies at different levels in the dam, it can be determined at what level the best quality is to be found. The water can then be abstracted from there and released into the river.

Inanda, the main and latest reservoir of the Mgeni System, is expected to remain the main source of water for the region until the year 2004. The Midmar Dam, completed in 1965, and the Albert Falls Dam, completed in 1975, are the two other major reservoirs which, together with the Henley and Nagle Dams, form the existing Mgeni System.

Data — Inanda Dam

Type	Composite: Concrete gravity and earthfill
Height above lowest foundation	54,5 m
Net storage capacity	242x10^6 m^3
Crest length	Spillway section: 140 m Concrete non-overspill: 208 m Earth embankment: 260 m
Type of spillway	Uncontrolled
Capacity of spillway	4 000 m^3/s
Surface area at full supply level	1 440 ha

6 Wolwedans Dam

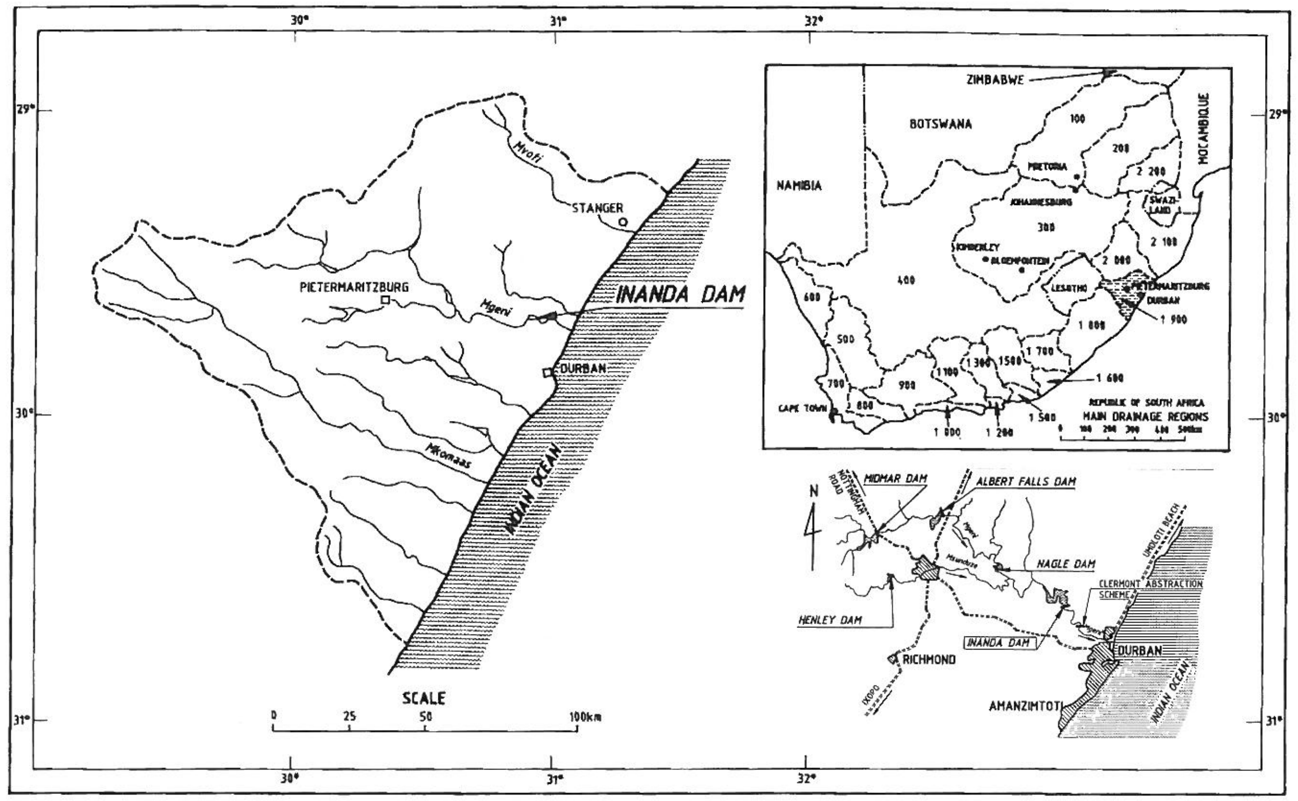
The Wolwedans Dam on the Great Brak River near Mossel Bay was completed in 1989. It was constructed mainly to supply water to the Mossgas plant that converts oil from the natural gas reserves below the ocean bed. This dam was the fifth dam in the country built with RCC, and one of the world's first two RCC arch-gravity dams, the other being the Knellpoort Dam in the Orange Free State.

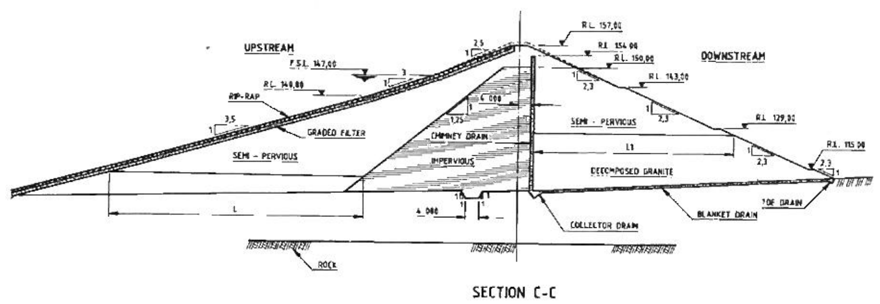
The Wolwedans Dam is also significant in that environmental considerations played a major role in the planning, design, construction and operation. The dam site was chosen after thorough investigations by the Department of Water Affairs, which included a comprehensive environmental impact report. The recommendations in the report were incorporated in the design of the dam to ensure that the project would minimise detrimental impacts on the environment. The Great Brak River Environmental Study Committee was also established and it conducted an environmental study with the objective of developing a management plan for the estuary.

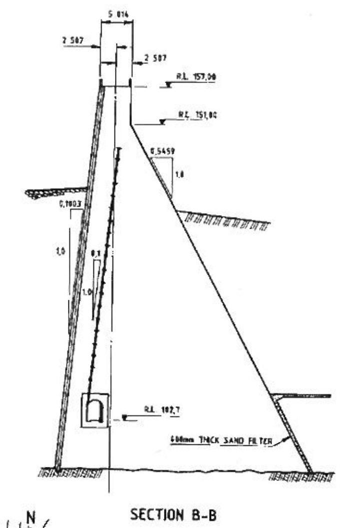
Data — Wolwedans Dam

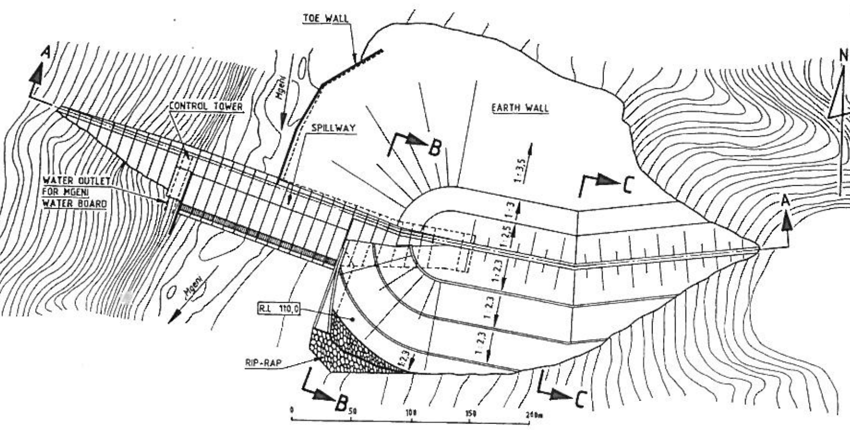
Type	Rollcrete arch/gravity
Height above lowest foundation	70 m
Gross storage capacity	24x10^6 m^3
Crest length	270 m
Arch radius	135 m
Total volume of RCC	178 000 m^3
Total volume of mass concrete	22 500 m^3
Total volume of reinforced concrete	9 800 m^3

Inanda Dam



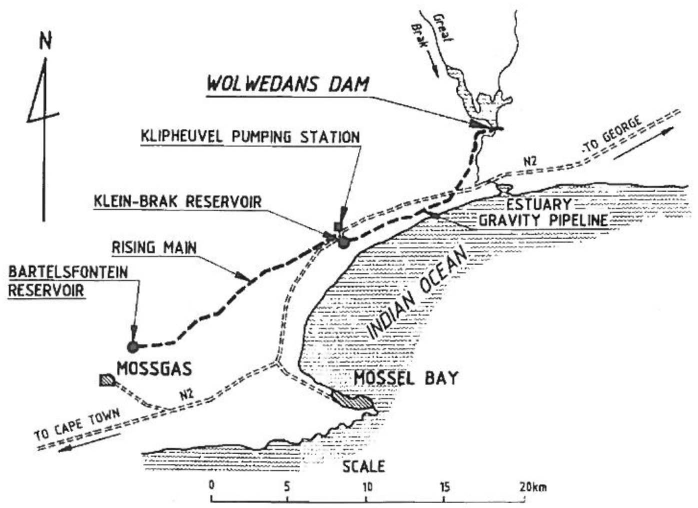




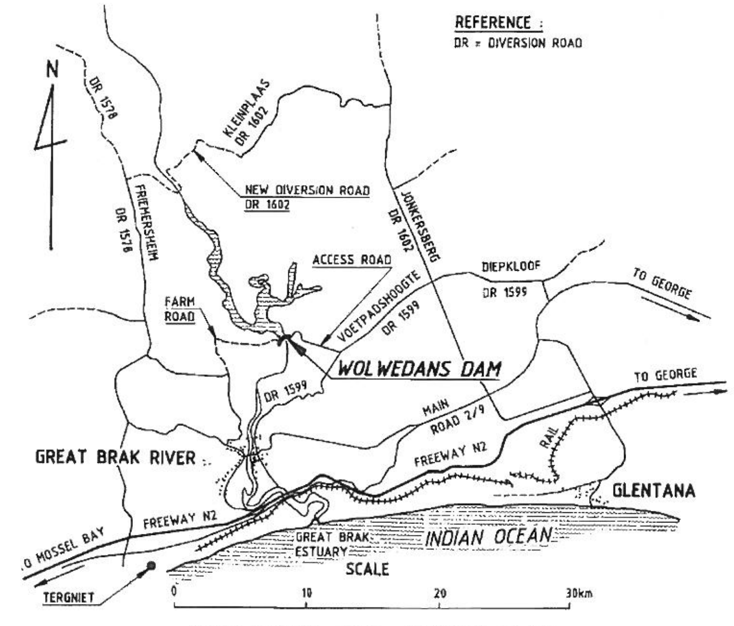


Plan of dam

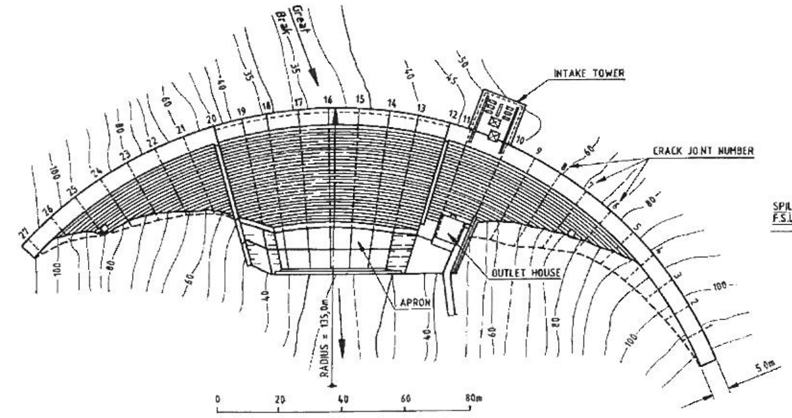
Wolwedans Dam



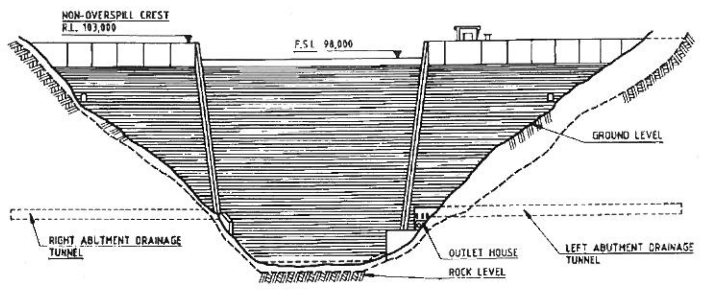
MOSSEL BAY GOVERNMENT WATER SCHEME
PROJECT LOCALITY MAP



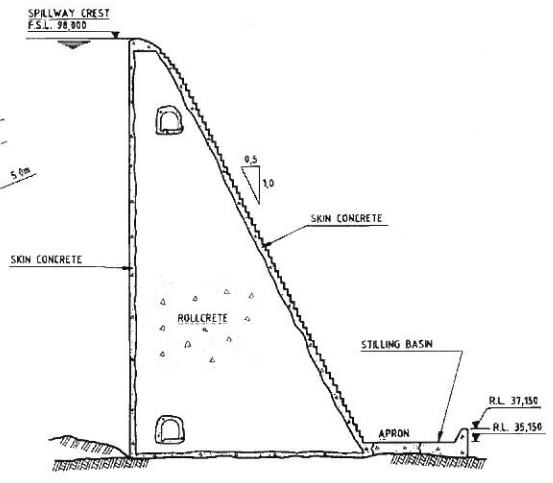
WOLWEDANS DAM : VICINITY PLAN



PLAN OF WOLWEDANS DAM



DOWNSTREAM ELEVATION



MAX. SECTION ON ℄

RCC placements	Average: 2 450 m^3 per 24-hour shift Peak: 2 994 m^3 per 24-hour shift
Type of spillway	Uncontrolled ogee
Spillway capacity (uncontrolled)	1 920 m^3/s
Reservoir surface area at full supply level	110 ha

THE ORANGE RIVER SYSTEM

The Orange River Project, South Africa's first multi-purpose water resource scheme, was announced in March 1962. The then Secretary of Water Affairs wrote in the White Paper on the Project:

The Project will serve the part of the Republic where water supplies for the primary consumptive needs for agriculture, industry and urban communities will for all time in the future constitute the limiting factor in the development of the country.

7 Hendrik Verwoerd Dam

The Hendrik Verwoerd Dam creates the major storage volume in the Orange River scheme, and is the first internationally designed and constructed large dam in South Africa. Soon after completion (in 1971), it overflowed in time for its official opening in March 1972. It is the dam with the largest reservoir capacity in the country. The dam wall is of the double-curvature concrete arch type with gravity abutments at either flank. Each abutment houses three intake blocks containing the equipment to control the release of water from the reservoir through the six chute spillways as well as by means of irrigation and river outlets. The central uncontrolled spillway provides additional flood discharge capacity. The foundation of the main arch portion incorporates an interesting heel support structure.

Provision was made for the future raising of the dam. Apart from its companion dam, the PK le Roux Dam, the Orange River Project also comprises the Orange-Fish Tunnel, at one time the longest continuous water tunnel in the world (83 km). This tunnel carries water from the Hendrik Verwoerd Dam to the Great Fish and Sundays River Valleys in the Eastern Cape.

Data — Hendrik Verwoerd Dam

Type	Concrete double curvature arch dam
Max height above lowest foundation	88 m
Full supply level	1 258,8 m
High flood level	1 264,9 m
Gross capacity of reservoir	5 958x10^6 m^3
Crest length	
Volume content of dam	1 730 000 m^3
Type of spillway	Various
Discharge capacity of outlets at high flood level	7 930m^3/s
Uncontrolled spillway	
6 floodgated chute spillways (radial gates)	8 310 m^3/s
Other outlets	1 200 m^3/s
Total outflow capacity	17 440 m^3/s
Area of lake at full supply level	37 400 ha

8 PK le Roux Dam

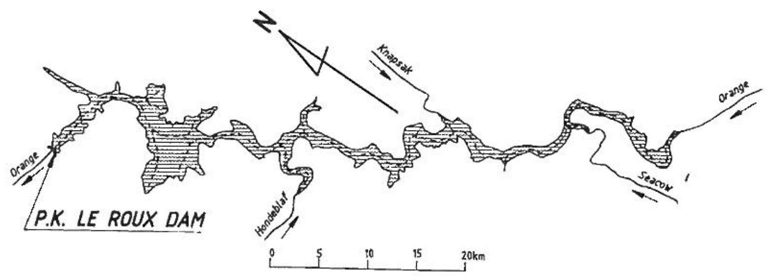
This dam, one of the major components of the Orange River Project, is the highest dam in the country, with the largest spillway. It is also the first large overseas-designed arch dam to be built in house by the Department of Water Affairs. This multipurpose structure (water supply irrigation and power generation) was completed in 1977 and has outlets on both flanks for supplying irrigation water to the canal systems. At the left flank the intakes are located supplying water to the underground hydro-electric power station. Construction of the hydro component, as at the Hendrik Verwoerd Dam, was managed by the Electricity Supply Commission (ESKOM).

The PK le Roux Dam is similar in design to the Hendrik Verwoerd Dam, except that it has four floodgates and chutes on the left bank and none on the right. The site, being narrower, lends itself better to an arch structure than that of the Hendrik Verwoerd Dam, and although 20 metres higher than the latter, it required only two-thirds the volume of concrete.

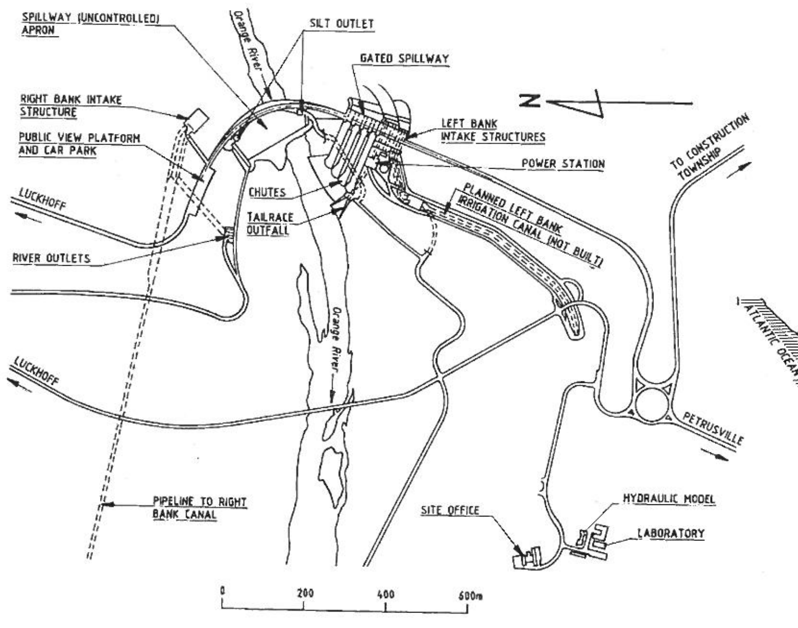
Data — PK le Roux Dam

Type	Double-curvature arch dam with gravity concrete left flank wall
Max height above lowest foundation	107 m
Gross capacity of reservoir	3 255x10^6 m^3
Crest length	765 m
Volume of excavation	2 000 000 m^3
Volume content of dam	1 000 000 m^3
Type of spillway	Various
Discharge capacity of outlets at High Flood Level:	
Uncontrolled	13 500 m^3/s
4 floodgated chute spillways (radial gates)	8 500 m^3/s
Total outflow capacity	22 000 m^3/s

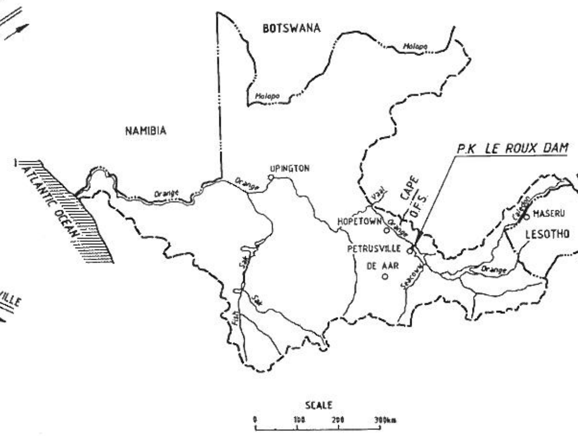
PK le Roux Dam



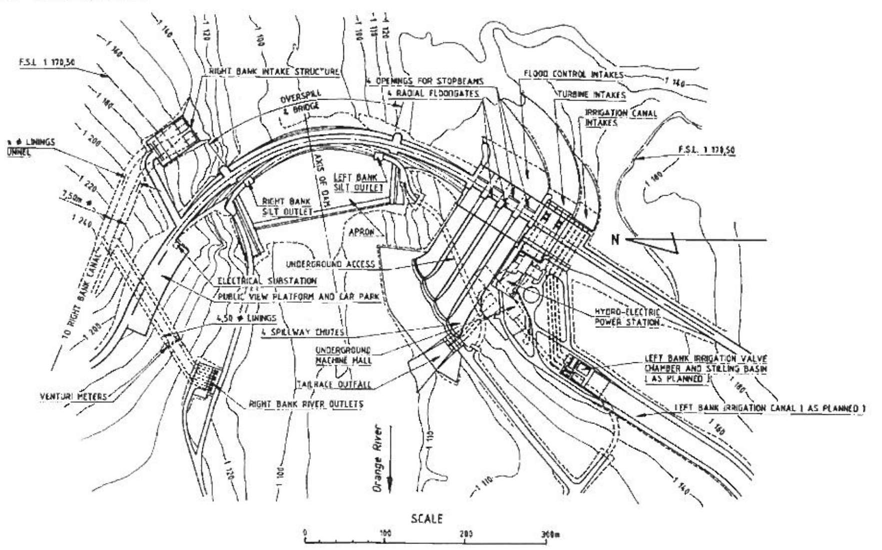
RESERVOIR BASIN



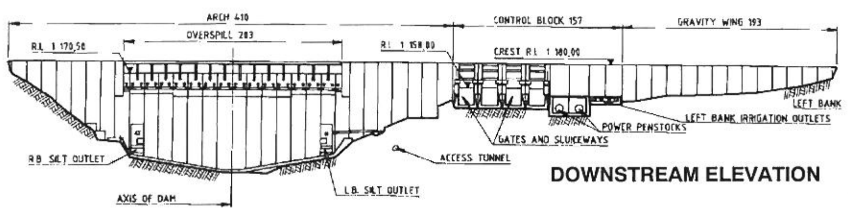
GENERAL SITE LAYOUT



LOCALITY PLAN



PLAN OF DAM



DOWNSTREAM ELEVATION

THE VAAL RIVER SYSTEM

The Vaal River System is the major water supply system in South Africa, as it is situated in the most economically active and most densely populated part of the country. Because of its important role in the national economy, the Vaal River System, comprising several dams, is planned and managed as a unitary system. It is described in more detail in Chapter II.

9 Vaal Dam

The Vaal Dam is one of three main storage units on the Vaal River, the other being the Grootdraai and Bloemhof Dams. It stabilises the flow of the Vaal River, thereby assuring water supply downstream of the dam. Water is supplied for domestic and industrial use, irrigation, thermal power generation and mining purposes.

Even though it is only the fourth largest dam in the country in terms of gross storage capacity, the Vaal Dam is without doubt the most important dam in view of its role as the primary supplier of water to the economic heartland of the RSA. It is also the hub of the Vaal River System, which is to be augmented in the future by the Lesotho Highlands Water Project.

The Vaal Dam was completed in 1938, but by 1951 the demand on the reservoir had grown to such an extent that it was decided to raise the dam wall by 6 m. This was achieved by increasing the height of the overspill section by 3,05 m and the installation of crest gates of 3,05 m high on the raised overspill section. The reservoir was then able to store 2 189 million m^3 at full supply level.

In the following years it became clear that the ever increasing demand was not the only problem facing the dam, but that floods created a very serious problem in that flood releases from the dam posed a threat to, *inter alia*, parts of Vereeniging adjacent to the river. When it was clear by the late 1970s that a further raising was necessary, it was decided to deal with the question of temporary flood water storage at the same time, so that it would be possible to reduce incoming flood peaks to more modest outflow releases.

The subsequent raising of the dam in 1985 by a further 3,05 m, of which 1,1 m is used for permanent storage, increased the permanent volume of the reservoir to 2 536 million m^3. This raising was effected by replacing the 60 old crest gates with 60 modern crest gates with a height of 6,68 m each. The main wall was also thickened, and strengthened by poststressed cables, and deep drainage provided, all for structural reasons, while the cascade type stilling basin was widened and its training wall heightened to accommodate larger design floods. The earthfill section was raised at the same time by 2,76 m, incorporating a curved concrete wave deflector.

The Vaal Dam is a composite dam consisting of a concrete gravity wall, 714 m long and 63,4 m high, and main and subsidiary earth embankments. The concrete wall consists of a gated spillway and a non-overspill section. The 60 crest gates are installed on top of the spillway section. Each slab-and-roller-type gate is controlled at the gate itself and can be opened at short notice to release incoming flood water. There is also central control of all gates from one station.

In addition to the creation of a temporary flood absorption capacity in the Vaal Dam with the most recent raising, the Department of Water Affairs also erected a network of telemetry gauging stations at selected points in the catchment area. These stations are equipped to transmit rainfall and flood observations by radio to a master station at the Vaal Dam and from there also transmit to Head Office in Pretoria.

Data — Vaal Dam

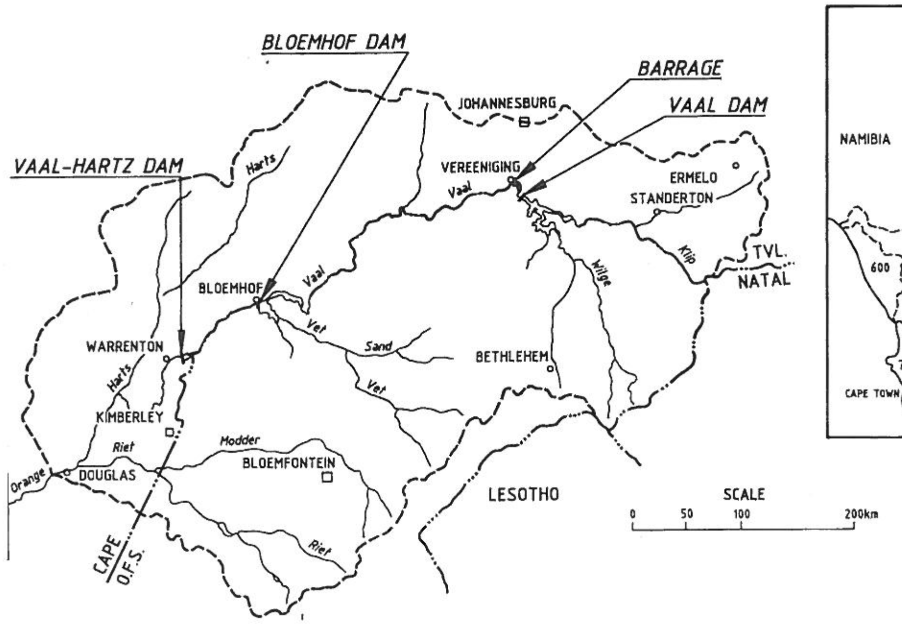
Type	Concrete gravity and earthfill
Height above lowest foundation	63,4 m
Gross storage capacity	2 536x10^6 m^3
Crest length: *Concrete*	714 m
Earthfill:	1 970 m
Secondary earthfill:	910 m
Type of spillway	60 controlled crest gates
Capacity of spillway	12 500 m^3/s at HFL
Surface area of reservoir full supply level	32 060 ha

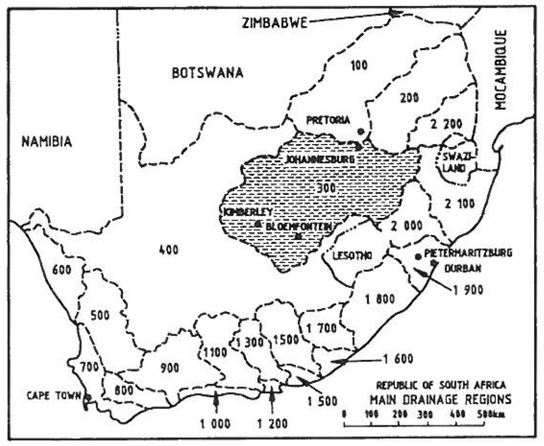
The raising of the Vaal Dam over the years was unfortunately not sufficient to provide for the increasing water needs. Therefore other plans had to be made to transfer water from the catchments outside the Vaal River basin. The first of these schemes was the transfer of water from the Tugela River across the Drakensberg to the Sterkfontein Dam. The maximum transfer capacity from the Tugela is 20 m^3/s at present.

The next scheme to bring additional water to the Vaal River basin was the Usutu-Vaal Government Water Scheme (Heyshope Dam), which has been supplying water to the Vaal River System from time to time since 1985. The Slang River Transfer Scheme (Zaaihoek Dam) was completed in 1989, and is capable of transferring 3 m^3/s of water via the Perdewaterspruit in the catchment of the Grootdraai Dam to the upper Vaal River.

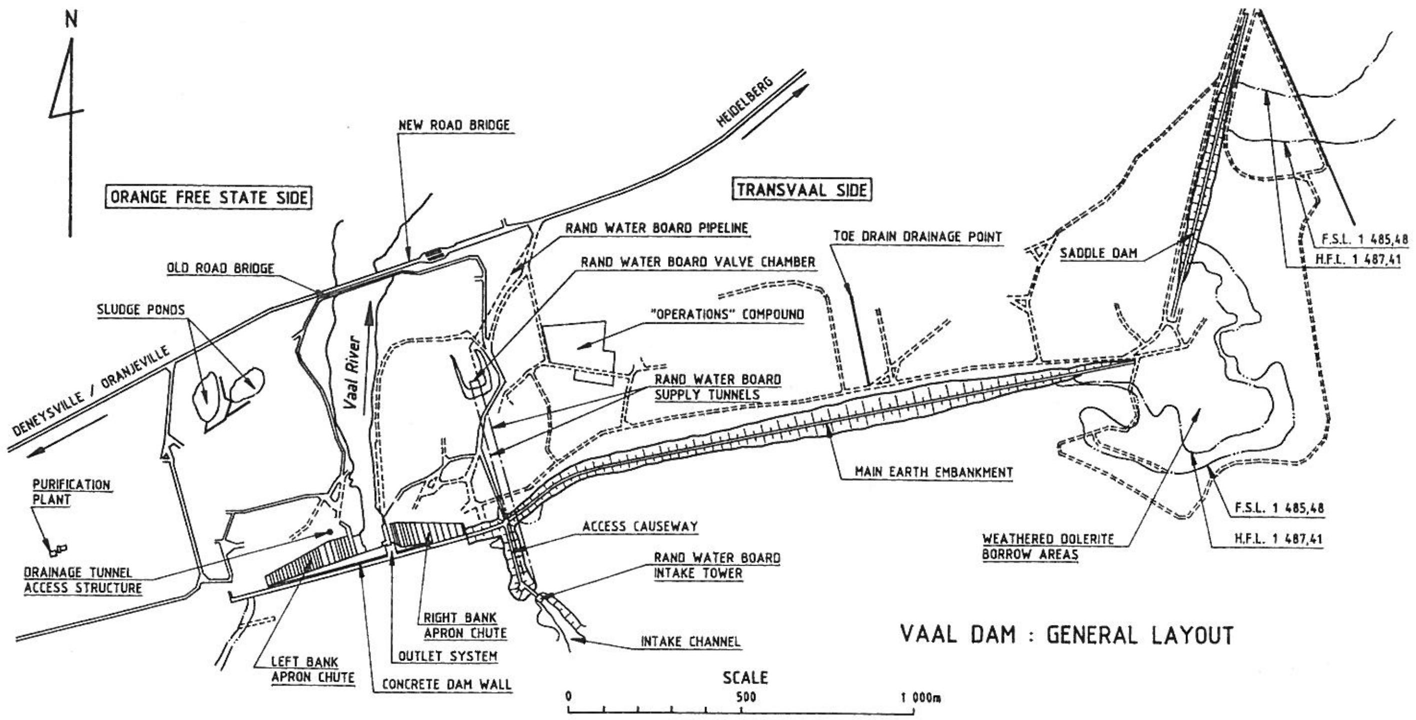
It is interesting to note that the Vaal Dam reservoir by itself is capable of a yield of about 29 m^3/s (908 million m^3/annum) on its own without the support of any of the supplementary schemes. By comparison, the joint system of transfer schemes plus the

The Vaal River System

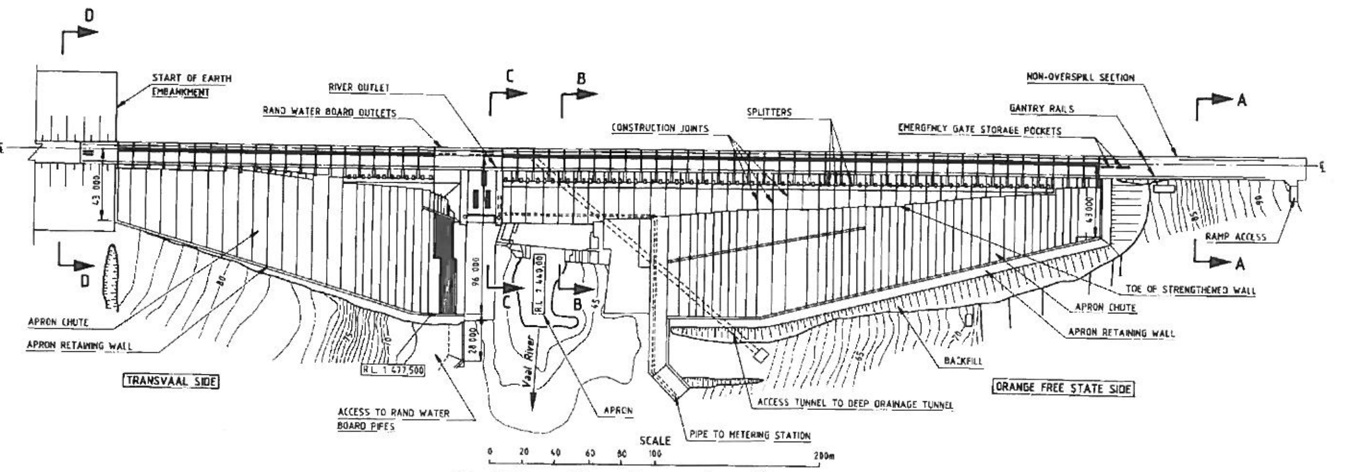




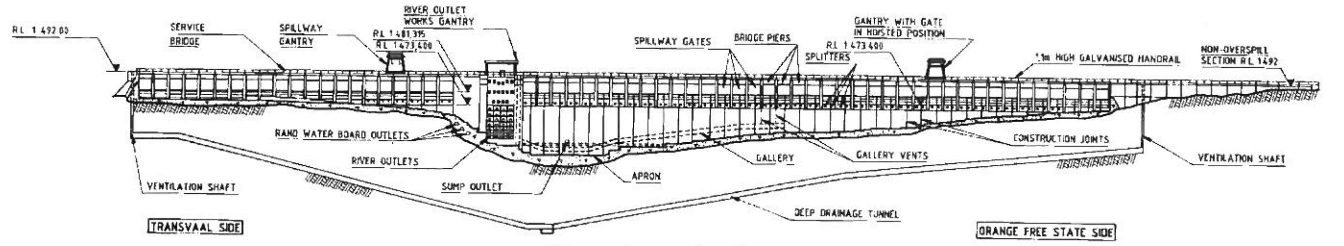
Vaal Dam



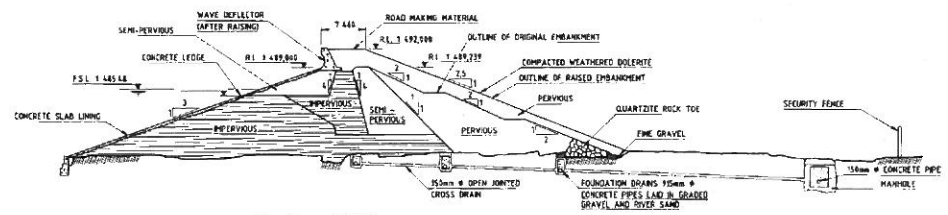
Vaal Dam



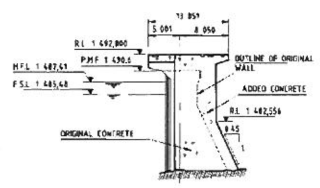
Vaal Dam: Plan of concrete wall



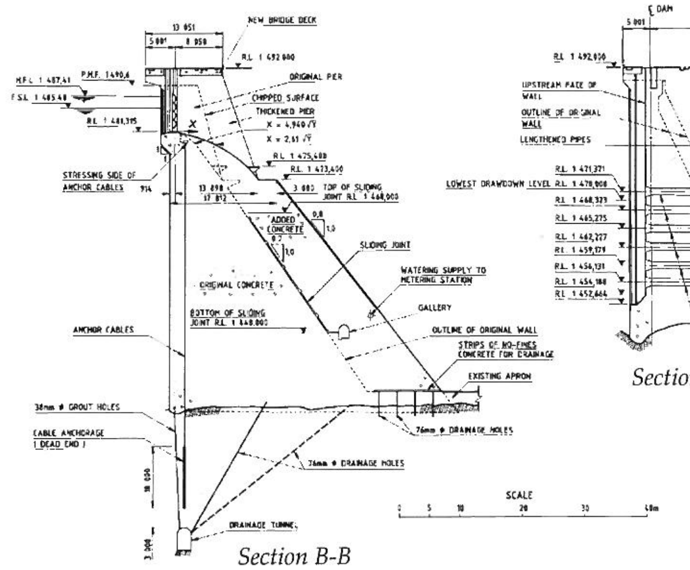
Downstream elevation



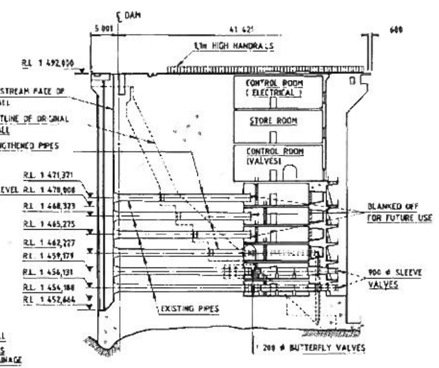
Section D-D



Section A-A

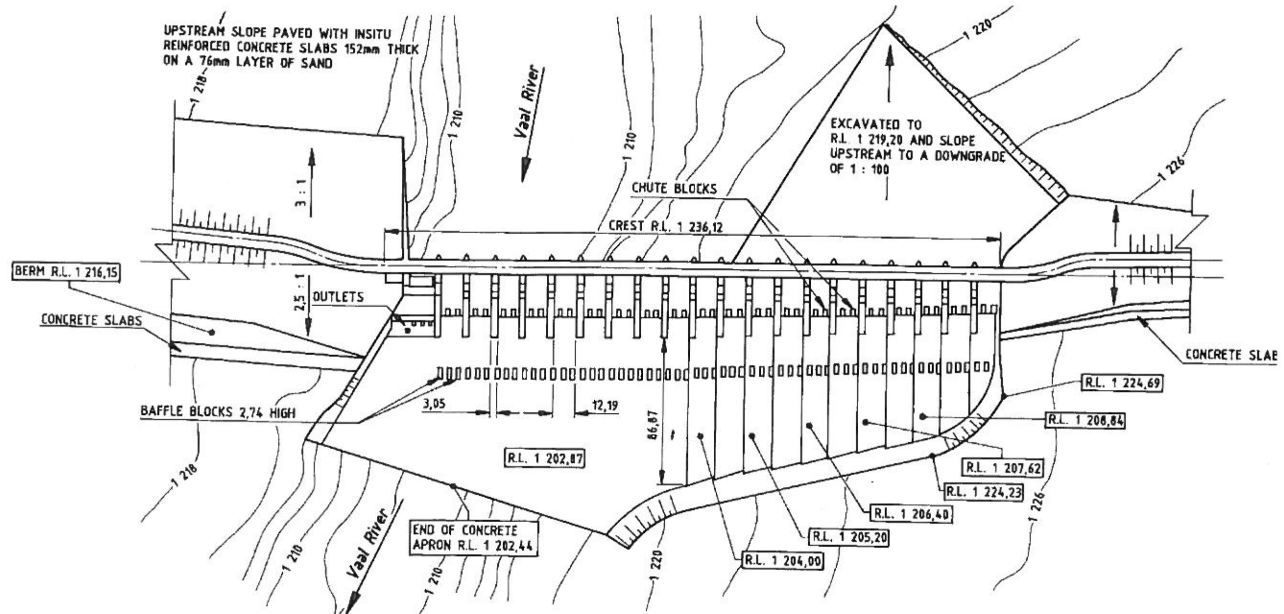


Section B-B

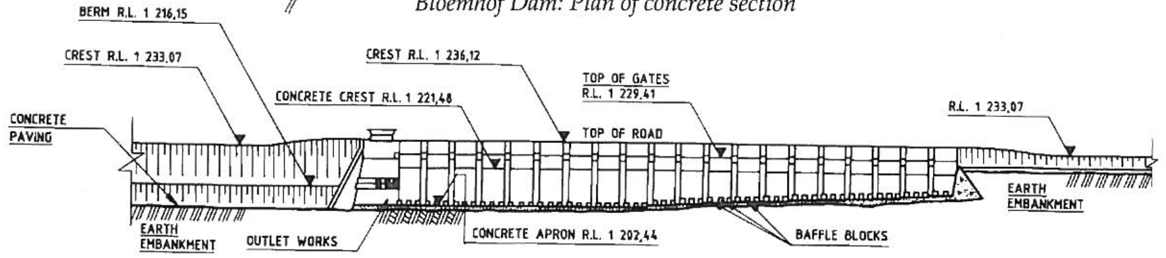


Section C-C

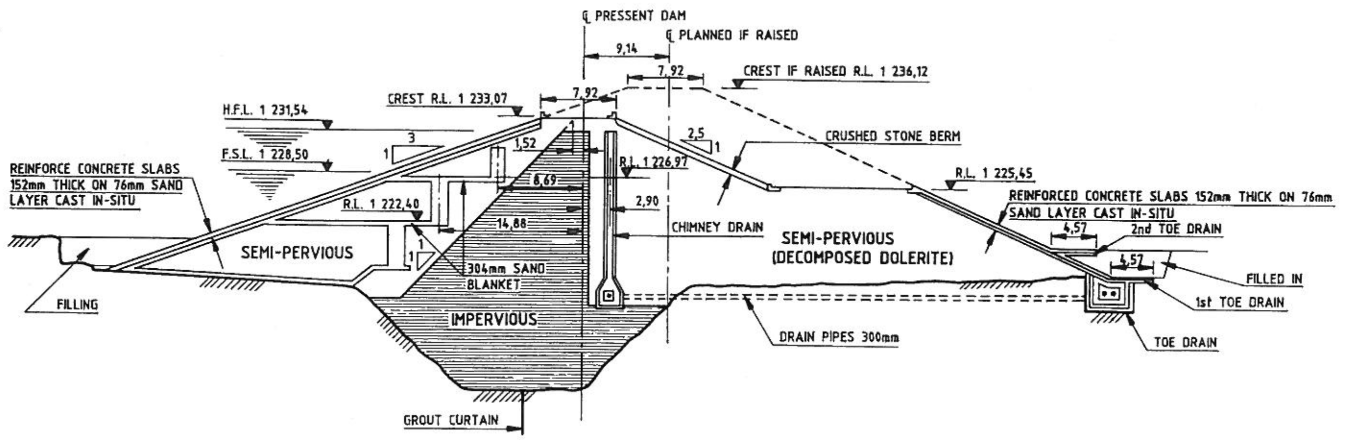
Bloemhof Dam



Bloemhof Dam: Plan of concrete section



Downstream elevation of concrete spillway section



Earth embankment: typical right bank section Bloemhof Dam

Grootdraai, Sterkfontein, Vaal and Bloemhof Dams' reservoirs are capable of maintaining a yield of 64 m^3/s. Even this quantity of water will, however, no longer be sufficient to provide for the total needs in the near future. The present demand from the Vaal Dam reservoir is over 40 m^3/s and the rest of the demand originates from users further downstream.

The Lesotho Highlands Water Project currently under construction will supply an additional 18 m^3/s by 1997 while the ultimate figure aimed at by the year 2020 will be about 70 m^3/s — more than the total current yield of the Vaal River System.

10 Bloemhof Dam

The Bloemhof Dam is situated on the Vaal River near the town Bloemhof, and forms the head reservoir of the Vaalharts Government Water Scheme, the largest irrigation scheme in the country, and consequently the largest single user of water from the Bloemhof Dam. It is one of 13 storage units in the Vaal River catchment, and serves to store and control the flow from the Vaal Dam and the catchment between Bloemhof and the Vaal Dam, an area of 69 374 km^2. This composite concrete gravity and earth dam is South African designed and constructed and is one of the longest dam structures in the RSA (4 720 m), and the volume of materials involved makes it one of the largest projects.

The concrete gravity river section is provided with 20 radial crest gates, each 12,19 m wide and 7,93 m high, to control floods of an estimated maximum value of 14 200 m^3/s. Three 1 680 mm diameter outlets are provided to release water for consumers down the river. Provision has been made for raising the dam by 3 m, which will increase the storage capacity to 2 090 million m^3, nearly double the present capacity and 90% that of the Vaal Dam.

In the construction of the concrete section of the dam and the large stilling basin below the wall, some 400 000 m^3 of rock was removed. A large amount of excavation was involved in the construction of the earth wall where the core trench was taken down to 20 m in the gravel layers underlying the river bed. During excavations for the wall, two old river beds were encountered and the earth moved during construction of the wall amounted to 4 million m^3; the most at any dam built in South Africa at that time.

A hydraulic model of the dam proved to be of great value in determining, *inter alia*, the optimum sequence in which the radial gates should be operated to avoid high scouring velocities, which would result from a high energy release at an unsuitable point. By following this sequence, it was possible to make use of a smaller stilling basin, with a consequent saving in cost.

The Bloemhof Dam supplies water to the Vaalharts weir, or barrage, which is situated 97 km downstream of the dam. This barrage then supplies the water to the Vaalharts Government Water Scheme.

Data — Bloemhof Dam

Type	Concrete gravity with earthfill flanks
Wall height above lowest foundation	35,2 m
Gross storage capacity	1 270x10^6 m^3
Crest length	4 270 m
Volume material in dam	
Concrete	25 000 m^3
Earthfill	2 760 000 m^3
Type of spillway	Crest 20 radial gates (controlled)
Spillway capacity	14 300 m^3/s
Surface area of reservoir at full supply level	22 270 ha

11 PALMIET PUMPED STORAGE PROJECT

The Palmiet River Government Water Scheme is the first phase of the development of this source for water supply to the Cape metropolitan area. It is a pumped storage scheme and, following the Tugela-Vaal Government Water Project, it is one of the many multi-purpose water projects in South Africa. It is a joint project of the Department of Water Affairs and ESKOM. Its dual purpose is to supply the Cape Town metropolitan area with water and to feed power into the national grid. The scheme will supplement the water supply to the metropolitan area by an initial 15 million m^3 of water annually and allow ESKOM to add 400 MW to the national installed power capacity.

Construction of the project commenced in 1983 and it consists of the following components:

11(a) The **Kogelberg Dam** is the lower storage unit and was constructed on the Palmiet River in an asymmetrical V-shaped valley. The dam consists of a mass concrete wall and a separate earth wall on the eastern flank. The concrete wall is an arch-gravity structure.

11(b) The **Rockview Dam** is situated above the Kogelberg Dam on the watershed between the Palmiet and Steenbras Rivers. This dam has virtually no natural catchment area and is solely dependent on pumping to fill it. Its basin is formed by two dam walls, the one is a rockfill while the other is an earthfill/rockfill wall, referred to as the main and northern embankments, respectively. The main embankment is a rockfill wall with a central clay core. The northern embankment is partly an earthfill wall built of sandy material with a clay core.

Power-station: A hydro-electric power-station with two 200 MW pump turbines is situated underground approximately 2 km upstream of the Kogelberg Dam wall.

Pumped Storage Project: The scheme is operated on a daily cycle, within a weekly cycle. From Saturday night until Monday morning, when the electricity demand is low, water is pumped from the Kogelberg Dam into Rockview Dam, to fill the dam for the following week's power-generating cycle. During the Monday-to-Friday peak periods, power is generated by releasing water from the Rockview Dam to the Kogelberg Dam to actuate the turbines.

Data — Kogelberg and Rockview Dams

Kogelberg Dam

Type	Arch-gravity concrete with separate earth embankment
Height above lowest foundation	54 m
Gross storage capacity	17,3x10^6 m^3
Crest length	182,5 m
Material content of wall	Concrete wall: 72 000 m^3
Earth embankment	202 000 m^3
Type of spillway	Ogee (uncontrolled)
Capacity of spillway	1 060 m^3/s
Surface area of reservoir at full supply level	142,6 ha

Rockview Dam

Type	Main embankment: Rockfill with clay core Northern embankment: Earthfill and rockfill with clay core
Height above lowest foundation	Main embankment: 48 m North embankment: 33 m
Gross storage capacity	16,8x10^6 m^3
Crest length	Main embankment: 1 300 m North embankment: 670 m
Material content of dam wall	Main embankment: 3 100 000 m^3 North embankment: 450 000 m^3
Type of spillway	None
Surface area at FSL	76,82 ha

12 Theewaterskloof Dam

The Theewaterskloof Dam forms part of the Riviersonderend-Berg River Scheme, an ingenious project which joins two catchment areas with plenty of water. The surplus runoff can then be discharged into a central storage dam so that, when the need for this water arises, it can be conveyed by gravity through a series of tunnels to where it is needed.

The interesting feature of the whole scheme lies in the fact that the flow can be reversed so that water from the Berg River can first be stored in the Riviersonderend valley and can then be conveyed back in the dry summer months to provide irrigation water in the supply area of the valley whence it originated. Water is supplied to the Cape Town metropolitan area as well as the urban areas of Stellenbosch and Caledon and to four agricultural areas in the Western Cape.

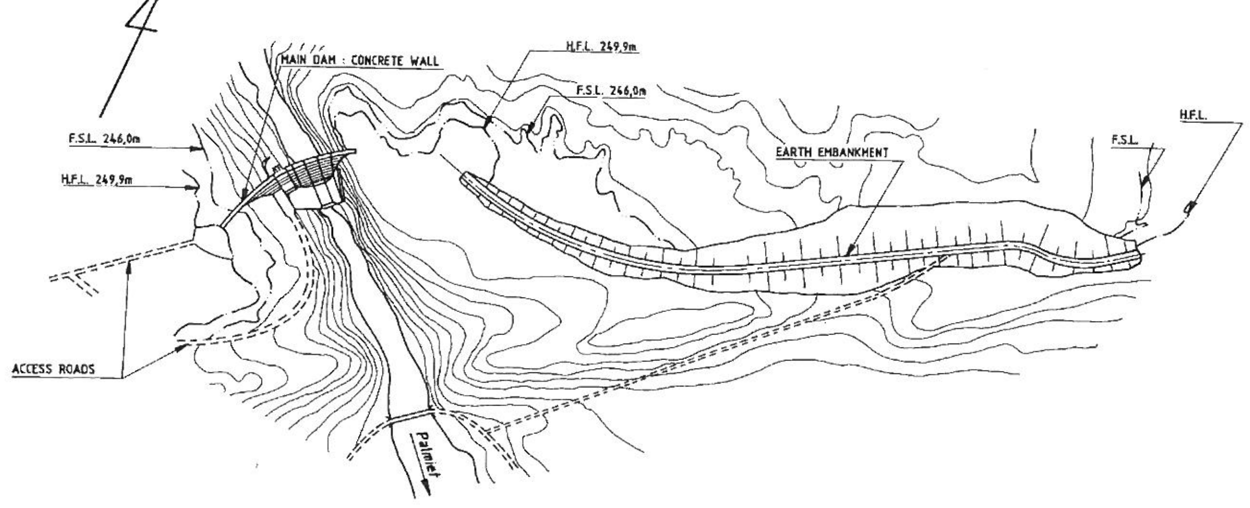
The Theewaterskloof Dam, completed in 1979, is an earthfill dam. A wall inside the dam basin houses the inlet and outlet of the Charmaine Tunnel from where the Franschhoek Mountain Tunnel starts. The Jonkershoek Tunnel outlet end releases water from the Theewaterskloof Dam into the Kleinplaas Dam when demand for water exceeds the available runoff from its own catchment area (the Eerste River) and the system, known as the Riviersonderend-Berg River transfer scheme, is one of the main supply sources of the metropolitan Cape Town area.

Although the Theewaterskloof Dam impounds the seventh largest reservoir in South Africa, it is relatively small, compared with the other six larger reservoirs. The Hendrik Verwoerd Dam, for instance, impounds a reservoir 12 times larger in storage capacity. The 470 000 m^3 of concrete placed on the project is only 40% of that used to build the PK le Roux Dam. This underlines the peculiar *bi-modal distribution* of South Africa's large dams, *one group of six dams are impounding reservoirs each over 1 000 million m^3 in storage capacity, which account for over half the total storage of RSA's large dams, and the rest are all impounding reservoirs each below 500 million m^3 in capacity (p 220).* The reason lies perhaps in the absence of suitable sites in the intermediate category.

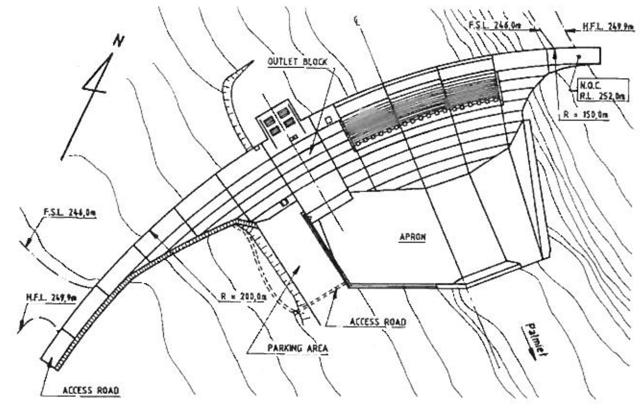
Data — Theewaterskloof Dam

Type	Earthfill
Height above lowest foundation	37,5 m
Gross storage capacity	482x10^6 m^3
Crest length	646 m
Type of spillway	Side-channel
Spillway capacity	390 m^3/s
Area at full supply level	5 100 ha

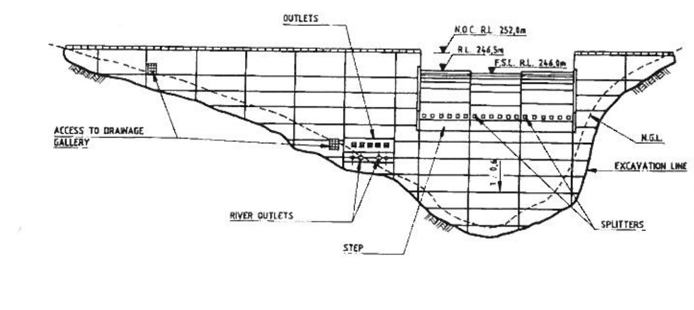
Kogelberg Dam



SITE PLAN
KOGELBERG DAM

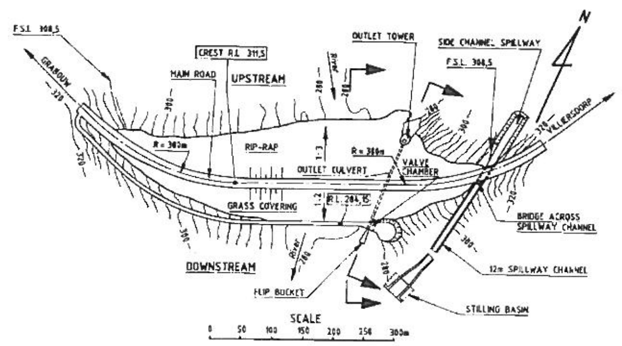


PLAN OF MAIN DAM
KOGELBERG DAM

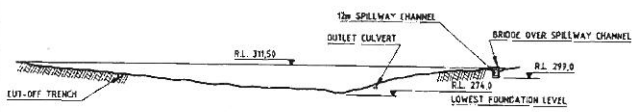


DEVELOPED SECTION ALONG EXTRADOS
KOGELBERG DAM

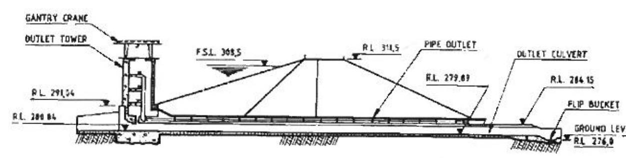
Theewaterskloof Dam



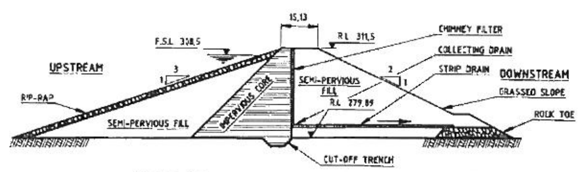
PLAN OF THEEWATERSKLOOF DAM



LONGITUDINAL SECTION



SECTION THROUGH INTAKE TOWER



SECTION THROUGH EARTH EMBANKMENT

SOME OLDER DAMS — EARLIER LANDMARKS

The **Woodhead** and **Hely Hutchinson Dams** on Table Mountain, completed in 1904, provided Cape Town with water long before schemes such as the Voëlvlei and Wemmershoek Dams and the Riviersonderend-Berg and the Palmiet River Projects were completed.

The **Lake Mentz, Lake Arthur, Grassridge** and **Van Ryneveldspas Dams** in the Eastern Cape were all built in the 1920s, mainly for irrigation purposes. Unfortunately they also have abnormally high sedimentation rates — a fact already recognised by a former Director of Irrigation, Dr AD Lewis.

The **Buchuberg Dam** and **Vioolsdrif Weir** were the first dams ever to be built on the Orange River for irrigation along the lower reaches of the river, including Noordoewer in Namibia.

The **Bulshoek** and **Clanwilliam Dams** on the Olifants River, Cape Province, were built especially to supply water to the Western Cape irrigation areas.

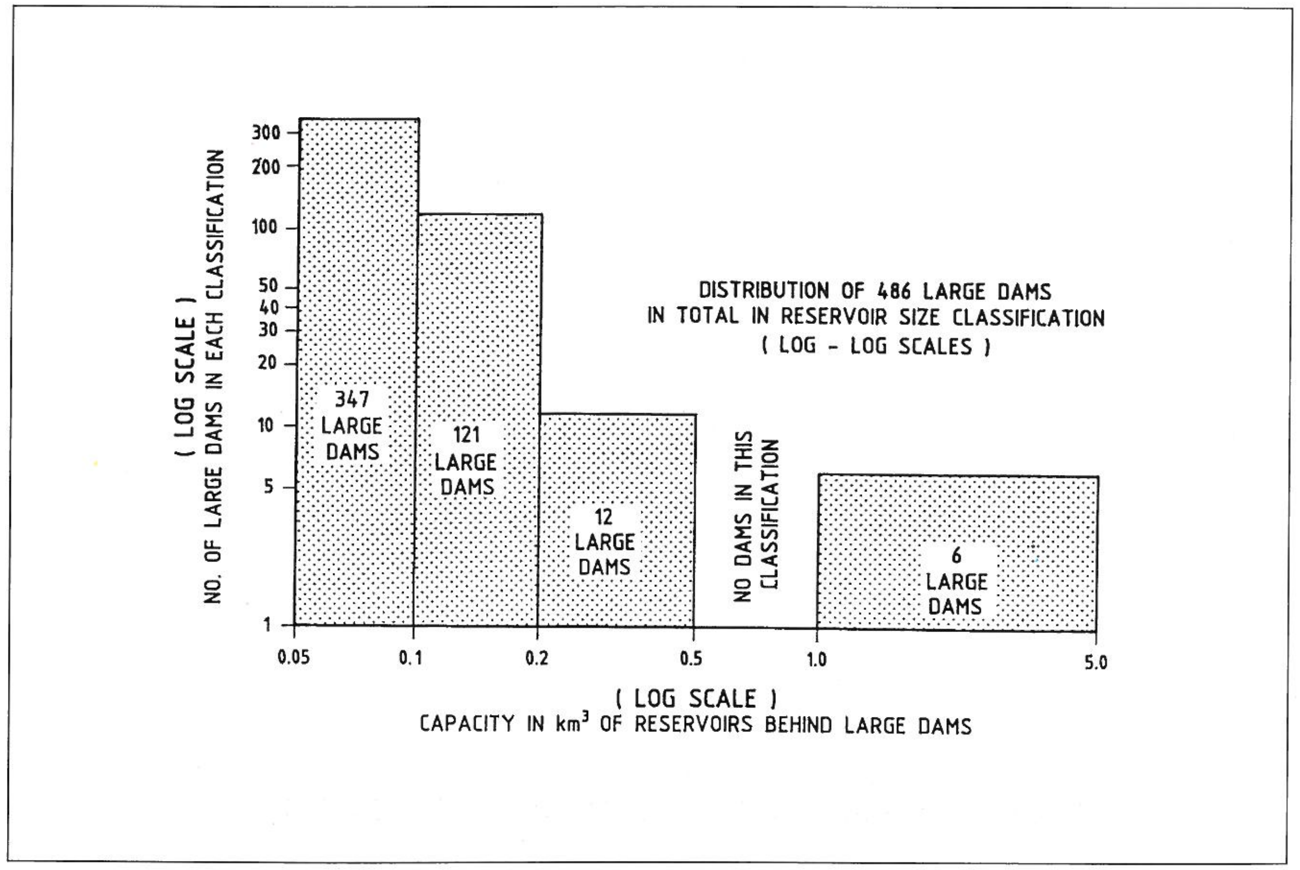
The **Henley, Shongweni** and **Nagle Dams** (Mgeni River) provided for the early needs of the metropolitan areas in Natal.

The **Groendal** (1932), and **Churchill** (1943) **Dams** were early dams built to provide Port Elizabeth with water. *(See also Chapter II, The Algoa System).*

The **Bongola Dam** was built for water supply to Queenstown, only much later followed by Xonxa, Waterdown, Lubisi, Bushmanskrantz and Oxkraal Dams, all on the Kei River System, in what was formerly known as the Ciskei and the Transkei regions.

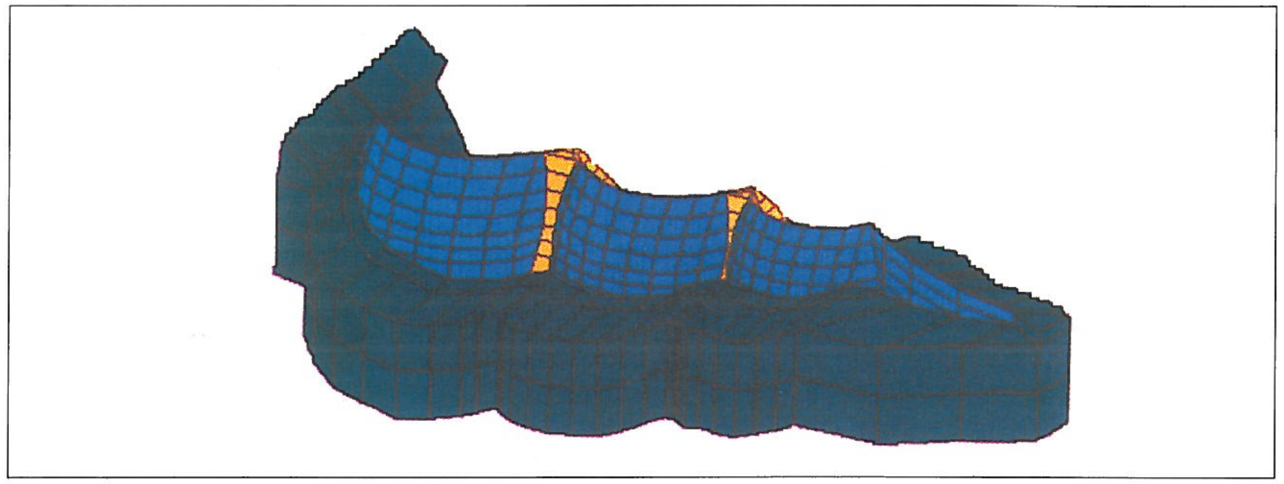
The **Laing Dam** was built for the East London area's water supply, later followed by Nahoon, Katrivier and Bridle Drift Dams on what is known as the Amatole River System.

The above landmark projects were taken as representative, but not exhaustive, of dam engineering in South Africa. In addition, some unusual dams, their problems or the solution are noted in the following section.

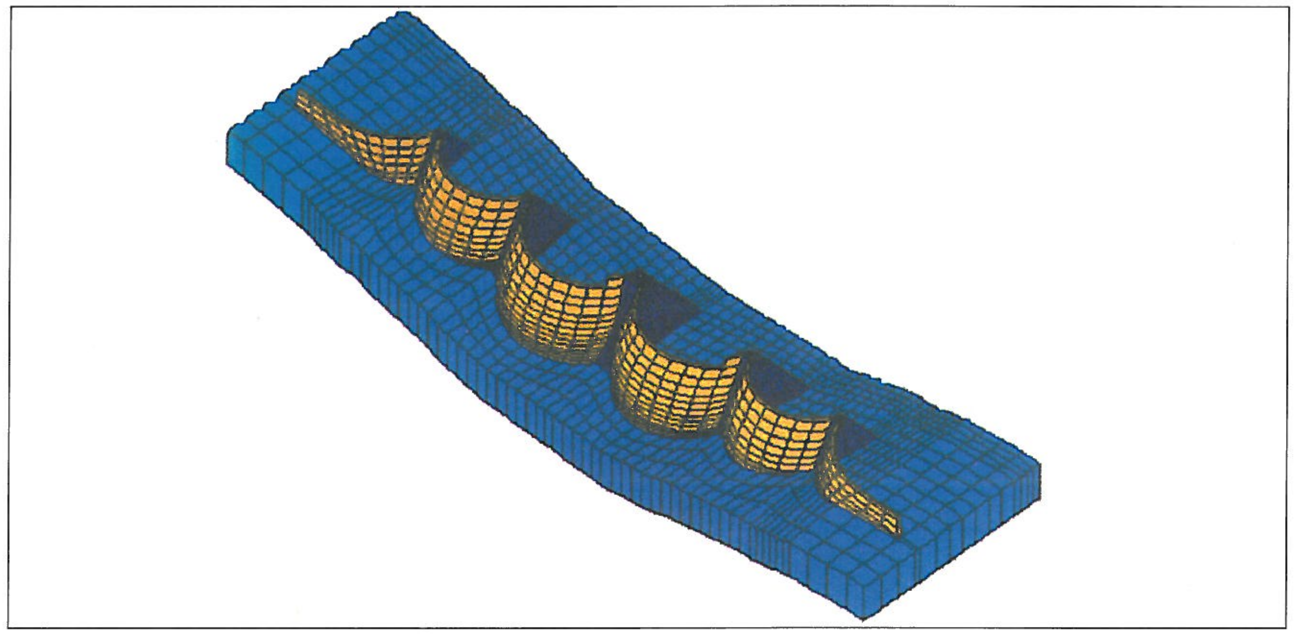


Capacity of reservoirs impounded by South African dams

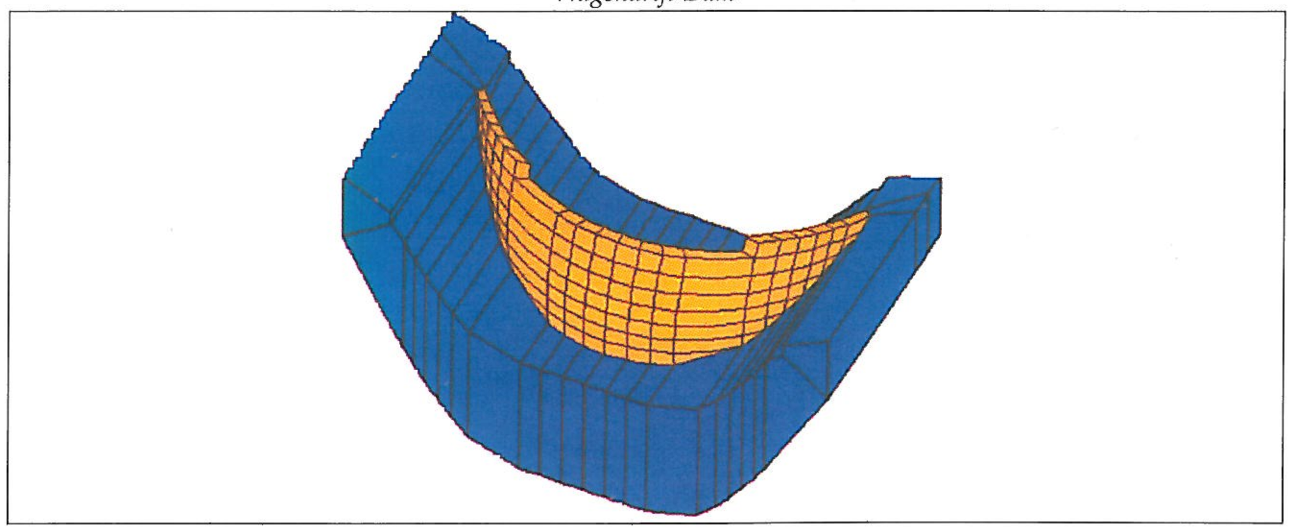
Double Curvature Arch Dams



Stompdrift Dam

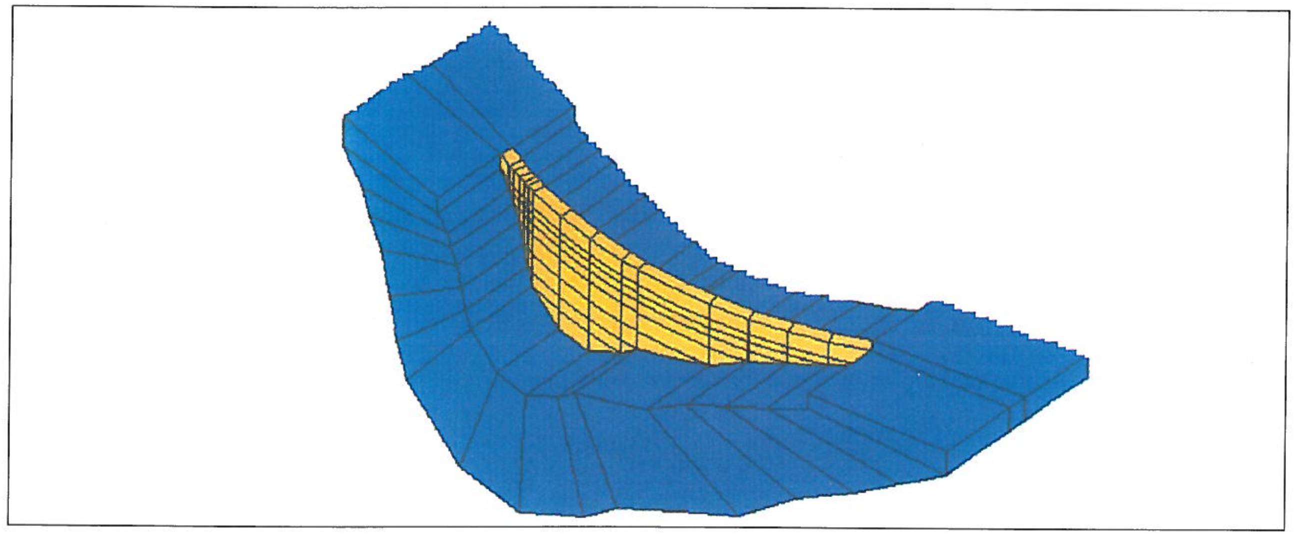


Wagendrift Dam

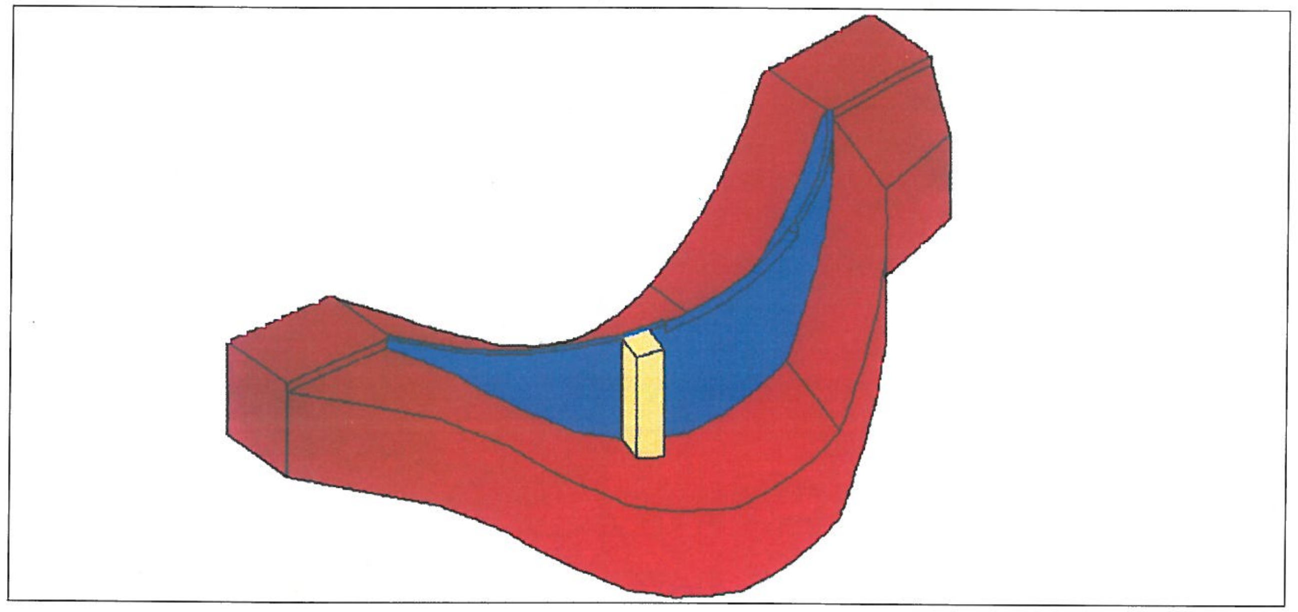


Paul Sauer Dam

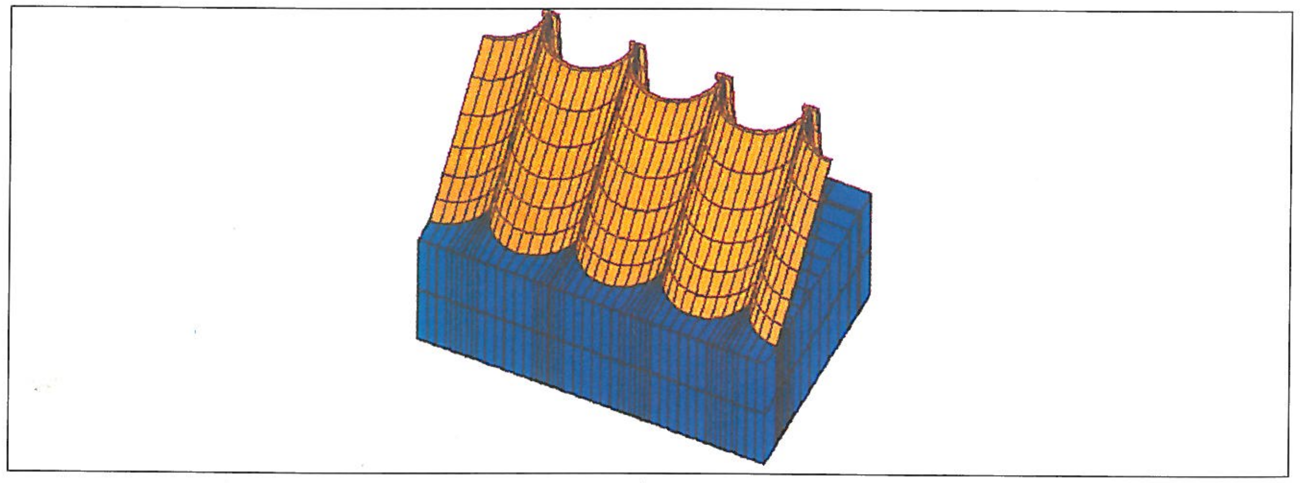
Single Curvature Arch Dams



Kogelberg Dam



Wolwedans Dam



Beervlei Dam

SOME UNUSUAL DAMS AND THEIR NOTABLE FEATURES

Phalaborwa and *Nooitgedacht dams* — desilting capabilities built in

Craigie Burn Dam — unusual thin shell dome cupola or double-curvature arch dam with earthfill embankments

Douglas Dam — labyrinth spillway

Jericho Dam — flap gates

Driekloof Dam — bi-directional spillway

Katrivier, Stompdrift and *Wagendrift dams* — triple cupola

Mockes Dam — syphon spillway

Grootdraai and *Morgenstond dams* — three types of spillway, including breaching sections

Driel Barrage — automatic gates (Merensky, 1979)

Steenbras and *Clanwilliam dams* — raised with poststressed cables

The five dams with the highest sedimentation levels in their reservoirs:

Welbedacht Dam — 85%; *Lake Mentz, Lake Arthur, Grassridge* and *Van Ryneveldspas dams* — 20% to 50%

Seven dams progressively raised (including by means of crest gates):

Vaal Dam (raised twice: by 6,1 m in the 1950s and by a further 3,05 m in 1985)

Loskop Dam (raised in 1979 by 9 m)

Vaalharts, Doorndraai and *Nzhelele dams* (fish-belly flaps, radial gates and fixed crest)

Clanwilliam Dam (poststressed cables and gates)

Steenbras Dam, raised four times, 6 m in 1924; 11,5 m in 1927; 1,35 m in 1954 and 6 m in 1957. The last raising was done by means of poststressed cables.

Dams already raised or gated or with future raising capabilities already built in:

Hendrik Verwoerd, PK le Roux, Bloemhof, Midmar, Paul Sauer (and many others).

Water, crystal-clear, cool and pure from groundwater sources: Little Karoo regional water supply scheme.

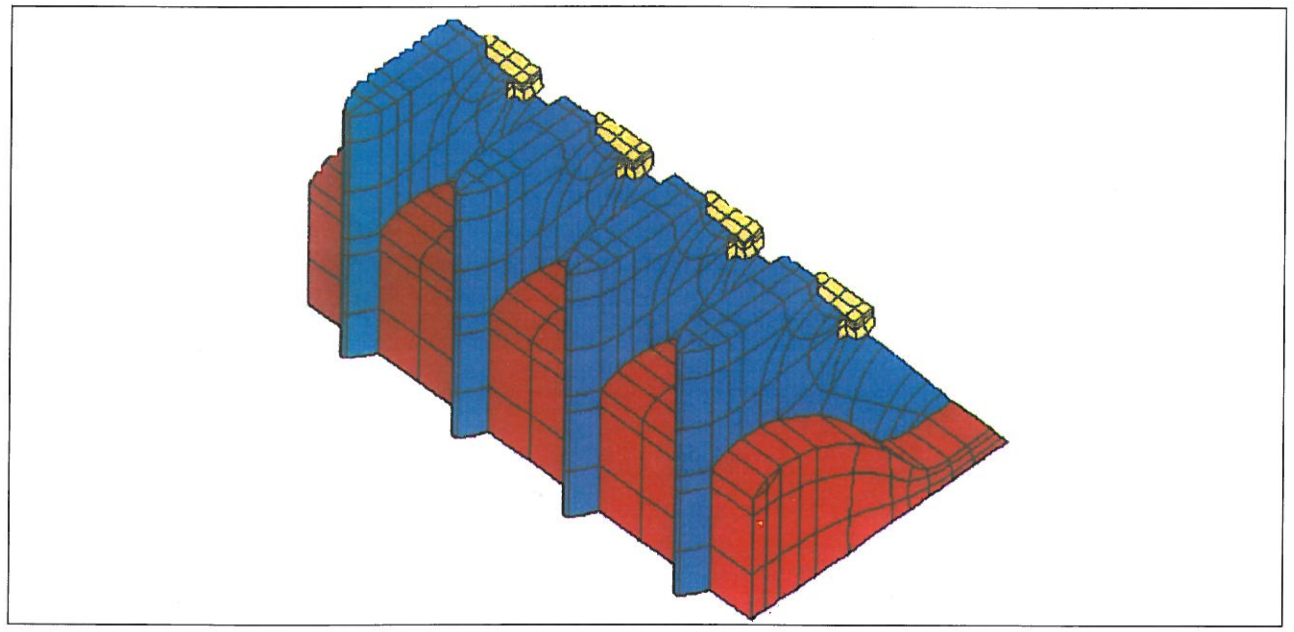
LARGE DAMS IN THE EASTERN CAPE PROVINCE (REGIONS FORMERLY KNOWN AS TRANSKEI AND CISKEI). (Olivier, 1977)

Umtata Hydro Electric Scheme: The rock and earthfill **Umtata Dam** on the Umtata River was completed in 1977. It is a multipurpose concept designed to meet the expanding needs of Umtata, the former capital of Transkei, as regards potable water and electricity supplies. Water for urban consumption is supplied from the dam through a pipeline to the municipal purification plant located on the right bank of the river close to the town.

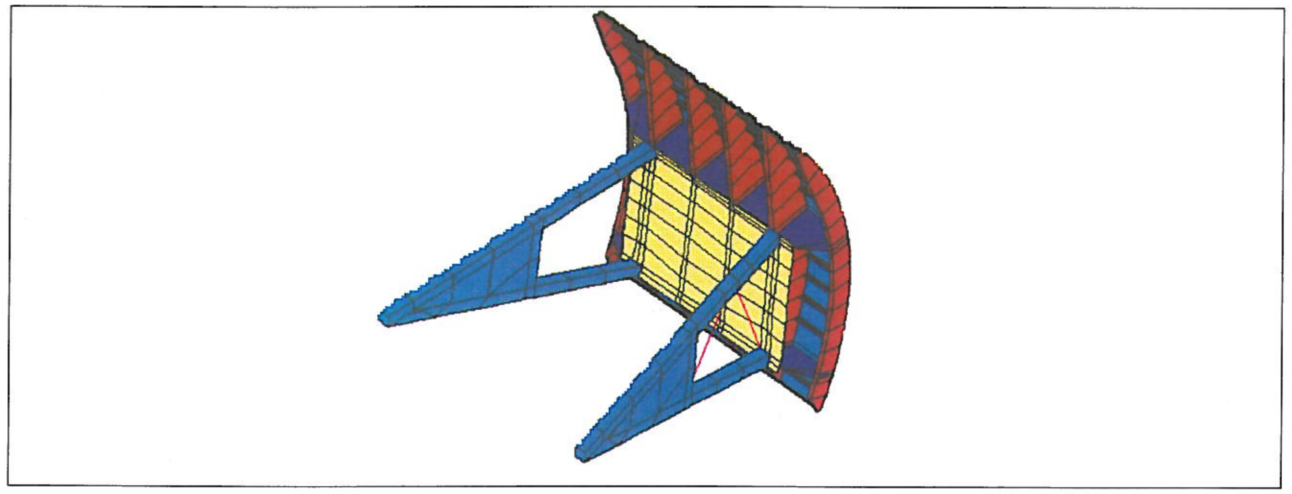
Lubisi Dam: The Qamata Irrigation Scheme was built in 1968 and comprises a storage dam (the Lubisi) on the Indwe River, as well as a diversion weir, the Lanti Weir, and a canal system. The dam is a double-curvature arch, 52 m high, and has a gross storage capacity of 156 567 000 m^3. It was designed and constructed by the Department of Water Affairs of South Africa.

Ncora Dam: This dam, completed in 1974, formerly known as Tsomo Dam, was the first large dam to be constructed on the Tsomo River. It stores water mainly for irrigation. Ncora is a concrete mass-gravity dam, 44 m high, with a gross storage capacity of 181 250 000 m^3.

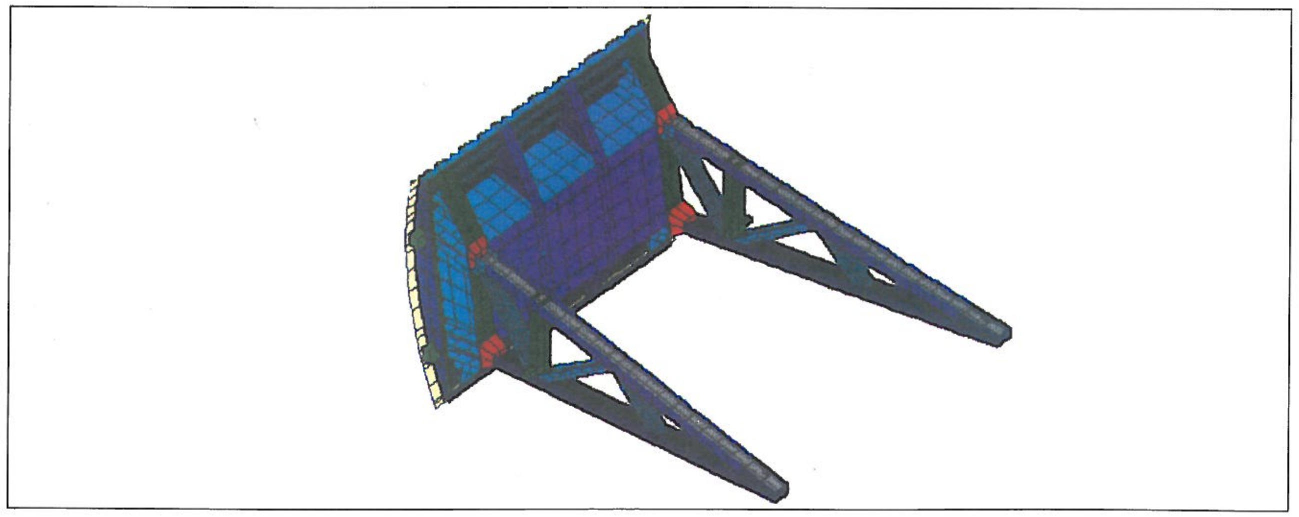
Radial Gate Control



Welbedacht Dam



Welbedacht Dam Gate



Pongolapoort Dam: Radial Gate — finite element analysis of structural lifting forces

SOME OTHER RECENTLY BUILT LARGE DAMS OF NOTE IN DEVELOPING REGIONS

Fika-Patso Dam: Located in the former Qwa-qwa, in a corner of the Orange Free State, close to the Lesotho and KwaZulu/Natal borders.

Bushmanskraal, Oxkraal and **Sandile Dams:** Located in the former Ciskei region, near Bisho.

MECHANICAL AND ELECTRICAL EQUIPMENT

The role of mechanical and electrical equipment is an important one in the creation, maintenance and operation of large dams as major functional elements in the water supply scenario of South Africa. For two reasons this warrants special mention:

- *Storage augmentation by means of crest gates* can often be achieved and is a more economical way of doing so than by physically increasing the height of the solid dam wall. *Controlled releases* of floodwaters and stored water is also an essentially mechanical/electrical function.

- *Sophisticated mechanical devices and service equipment* are essential to the construction and operation of large dams.

Storage augmentation

Economical raising of the full supply level of a dam and storage capacity in the reservoir created by it, can often be realised by the addition of crest gates to a large dam: radial, flap-type, slab and roller types of crest gates are the ones most commonly employed. Many dams have been so raised and some are being built at the outset in such a way as to make this addition possible at a future stage.

Examples:

Vaal Dam — twice raised by crest gates
Bloemhof Dam — crest gates installed at outset
Albasini, Doorndraai, Chelmsford Dams — raised by crest gates
Midmar Dam — raising by crest gates in future provided for
Hendrik Verwoerd and *PK le Roux Dams* — crest-gate raising allowed for in design
Vaalharts Weir, Jericho and *Bossiespruit Dams* —raised by flap-type or tube-type gates
Morgenstond Dam — raised by crest gates
Mentz, Welbedacht, Elandsdrift Dams — crest gates provided at outset

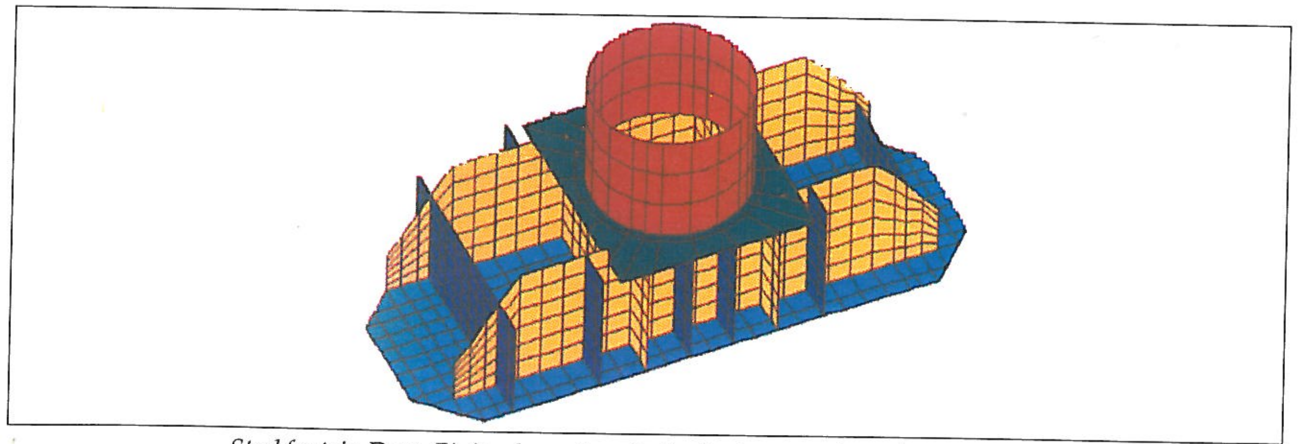
Controlled releases

Mid-level gates were installed for controlled releases at, for instance, the *Hendrik Verwoerd, PK le Roux* and *Woodstock dams* and bottom outlets at *Sterkfontein Dam*. Lower-level sluice valves are provided for sediment release, water supply and river flow compensation water. These are of the control, emergency, service and disperser types. They are also necessary for reservoir drawdown if needed for inspection.

Service equipment

Service equipment of the mechanical kind, closely associated with large dams, are items such as gantry cranes for handling emergency gates, stoplogs and trashrack rakes. Many varieties and sizes are prevalent in South African practice, including special equipment at underground and surface power-stations *(Drakensberg, Hendrik Verwoerd, PK le Roux)*.

The annexed tables give a survey of the main features of some of the representative equipment in the above two categories.



Sterkfontein Dam: Finite element analysis of gate-operating cylinder pedestal

GATES

PURPOSE	NUMBER	TYPE OF GATE	DAM
Crest control	3	Radial	Driel Barrage
Crest control	5	Radial	Welbedacht
Crest control	2	Radial	Elandsdrift Barrage
Crest control	60	Roller	Vaal
Crest control	20	Radial	Bloemhof
Crest control	13	Radial	Albasini
Crest control	11	Radial	Doorndraai
Crest control	10	Radial	Chelmsford
Crest control	3	Flaps	Vaalharts
Crest control	1	Drum	Jericho
Crest control	1	Pipe	Bossiespruit
Auxiliary spillway	6	Radial	Hendrik Verwoerd
Auxiliary spillway	4	Radial	PK le Roux
Auxiliary spillway	3	Radial	Pongolapoort
Service outlet	2	Slab	Sterkfontein
Emergency closure	2	Slab	Sterkfontein
Service outlet	1	Slab	Nooitgedacht
Service outlet	1	Jet flow	Hazelmere

SPECIAL OPERATING DEVICES

PURPOSE	NUMBER	TYPE OF DEVICE	DAM
Outlet for optimum draw-off	1	Telescopic tower (35 m high)	Ebenezer
Crest raising	1	Pipe gate	Bossiespruit
Gate downpull reduction	1	Slab with "nose"	Woodstock
Emergency outlet closure	Several	Spheres, double cones plus outlets	Hendrik Verwoerd and Floriskraal
In situ- maintainable valve	0	ISM valve	Not yet applied in actual service
Outlet, controlled	2	Buoyancy gates	Woodstock and Sterkfontein

VALVES (SERVICE)

PURPOSE	NUMBER	TYPE	DAM
River outlets	8	Jet disperser	Vaal
Compensation	1	Jet disperser	Kat River
Service	1	Jet disperser	Wagendrift
Service	1	Jet disperser	Stompdrift
Canal feed	4	Jet disperser	PK le Roux
Compensation	5	Jet disperser	Welbedacht

VALVE OR GATE (EMERGENCY)

PURPOSE	NUMBER	TYPE	DAM
Closure	1	Ball valve	Pongolapoort
Closure	1	Ball valve	Ebenezer
Closure	1	Slab gate	Brandvlei
Outlets, draw-down (silt)	8	Jet disperser valves	Hendrik Verwoerd
Outlets, draw-down (silt)	4	Jet disperser valves	PK le Roux

These gates, valves, servicing and hoisting equipment are generally fabricated to specification by international suppliers through local agents.

Electrical equipment

Part and parcel of every large dam's equipment installation is its electrical lighting and operating equipment. Electrical systems are installed to be operated from the mains supply, suitably stepped down, and are also backed up by an emergency diesel generator system. These electrical systems are essential for normal operation, flood control and maintenance of gates, valves, cranes, elevators, communication and flood-warning systems, and for structural monitoring and surveillance. Such systems are usually customised for each large dam and are generally supplied from available commercial sources. In some cases they are custom-built for the site.

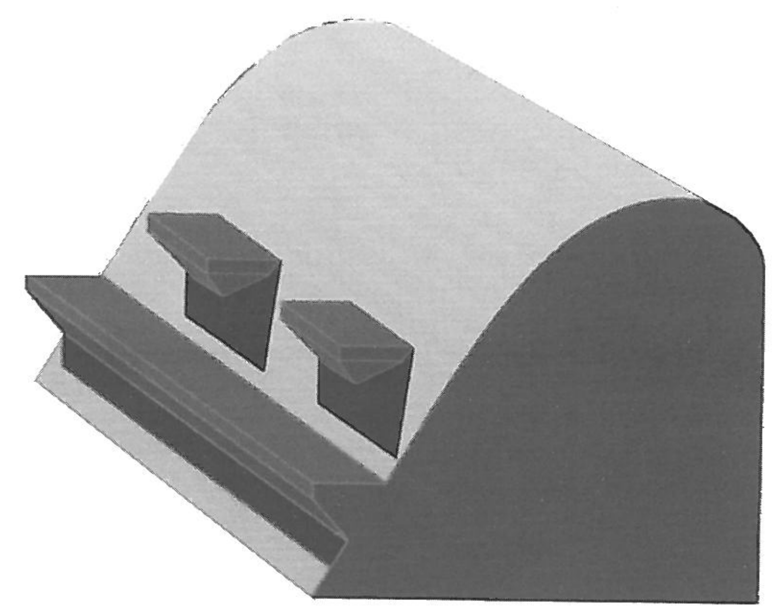
In special applications, such as water-power installations and pumping stations which are often incorporated in the main body of the dam, heavy mechanical and electrical equipment (closely associated with the dam and its function) is built in: turbines, reversible pump-turbines, pumps, special piping and valving and control and governing gear. These present features to the operator, owner and visitor alike that enhance the appeal of a large dam.

Examples:

Large hydropower-stations	Hendrik Verwoerd and PK le Roux Dams
Small hydro-power-station	Paul Sauer Dam
Pumped storage projects	Palmiet (Rockview and Kogelberg Dams) Drakensberg (Kilburn and Driekloof Dams).
Pumping stations	Steenbras, Grootdraai, Nooitgedacht, Vygeboom, Westoe, Jericho Heyeshope, *et al.*

Conclusions

The above review serves to emphasise that any large dam in South Africa, as elsewhere in the world, is dependent for its construction, function and safety on high technology in the hydro-mechanical and electrical engineering fields and that this is duly catered for. A few of the more unusual innovations are described and illustrated in the addendum on the next few pages.



THE ROBERTS CREST ENERGY DISSIPATOR FOR SPILLWAYS

HYDRAULIC ASPECTS OF SOUTH AFRICAN DAMS

An essential part of every dam is its capability of safely handling floods. Its principal ancillary works of permanent nature are therefore its spillway and middle or bottom outlet structures. To a lesser extent the flood-diversion technique employed during construction, merits mention, but as this is of a temporary nature, coffer-damming, bypassing and closure will not be discussed in this short section.

Handling floods involves a principal spillway (or flood passage), sometimes an auxiliary or secondary spillway and often also an emergency or breaching section. Examples of all these are found in RSA dams. A particular aspect that was given much attention is whether to equip dams with crest gates or not. As a general rule, crest gates are resorted to as a means of second stage raising of full supply level (Clanwilliam, Albasini, Doorndraai, Vaal and Midmar Dams). In some cases they are provided at the outset (Elandsdrif, Bloemhof and Roodekopjes Dams). Due to the danger of wrong operation they are not recommended for remote locations or where there is limited flood warning time. Ideally, a dam should be capable of letting floods pass safely even if all else fails. Some dams are equipped with uncontrolled as well as controlled spillways (Hendrik Verwoerd and PK le Roux Dams) and some even with emergency breaching sections (Grootdraai Dam).

The other aspect of letting floods pass safely is dissipating the energy downstream so that scour and erosion are minimized. Plunge pools are used for straight-drop overflow spillways (Pongolapoort, Hendrik Verwoerd) and/or chutes (with ski-jump extremities) controlled by radial gates (PK le Roux, Pongolapoort, Hendrik Verwoerd, Waterdown) or stepped overflows with stilling basin utilizing a hydraulic jump (Clanwilliam, Wolwedans). A South African development known as a Roberts crest energy dissipator or splitter-and-step, is employed in some 35 RSA dams to create turbulence and aeration in the overflowing nappe over an ogee crest (Loskop, Lakenvallei, Albert Falls, Erfenis, Allemanskraal). Due to the stepped downstream spillway slope at rollcrete dams the energy dissipating stilling basins or buckets are proportionately much smaller than for slopes with a smooth face (compare Floriskraal and Zaaihoek).

Emergency breaching sections are designed to progressively break away as the sloping clay core is overtopped (Morgenstond, Grootdraai). Some earthfill dams are provided with overtoppable embankment spillways (Spitskop, Loerie). Some fill dams are equipped with upstream rip-rap (Theewaterskloof) or

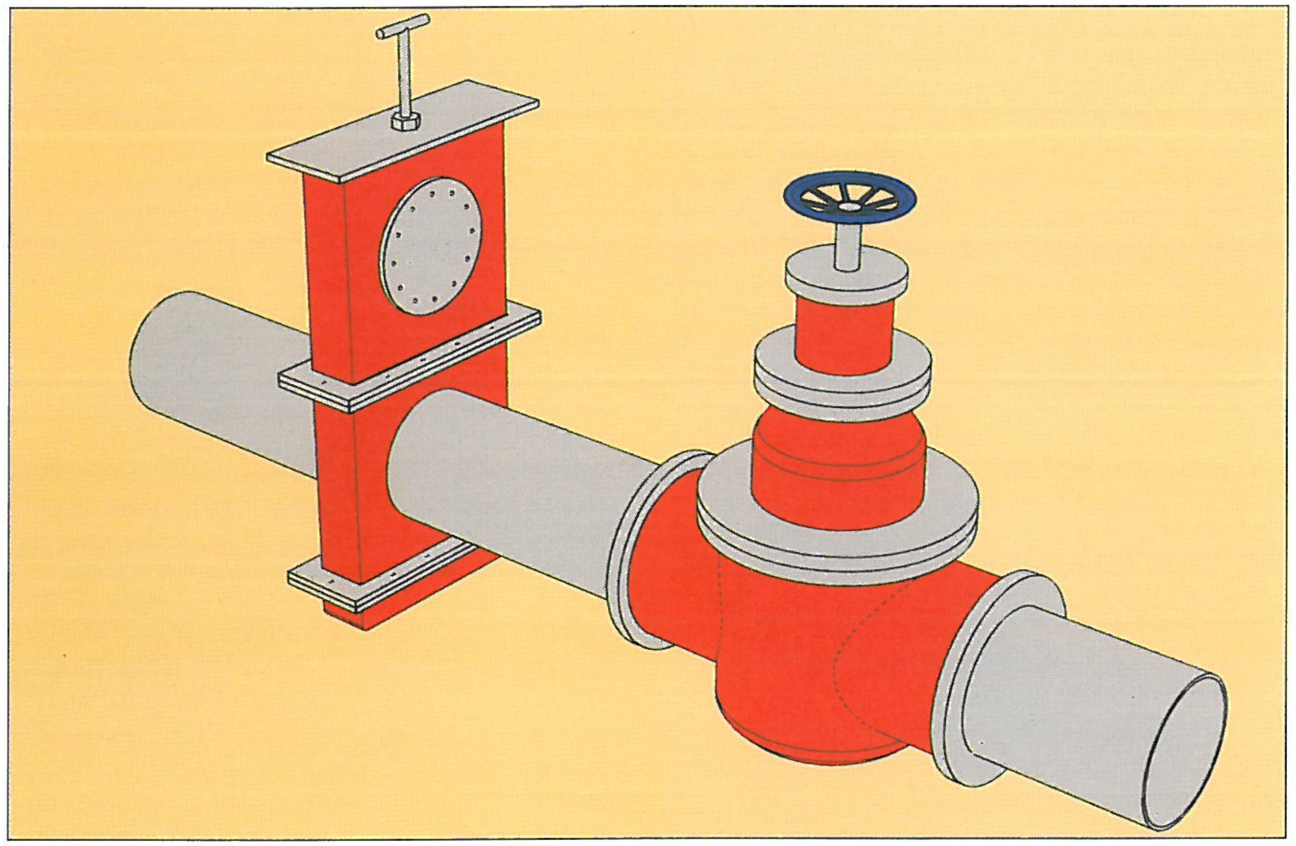


Figure 1: The in situ-maintainable (ISM) valve

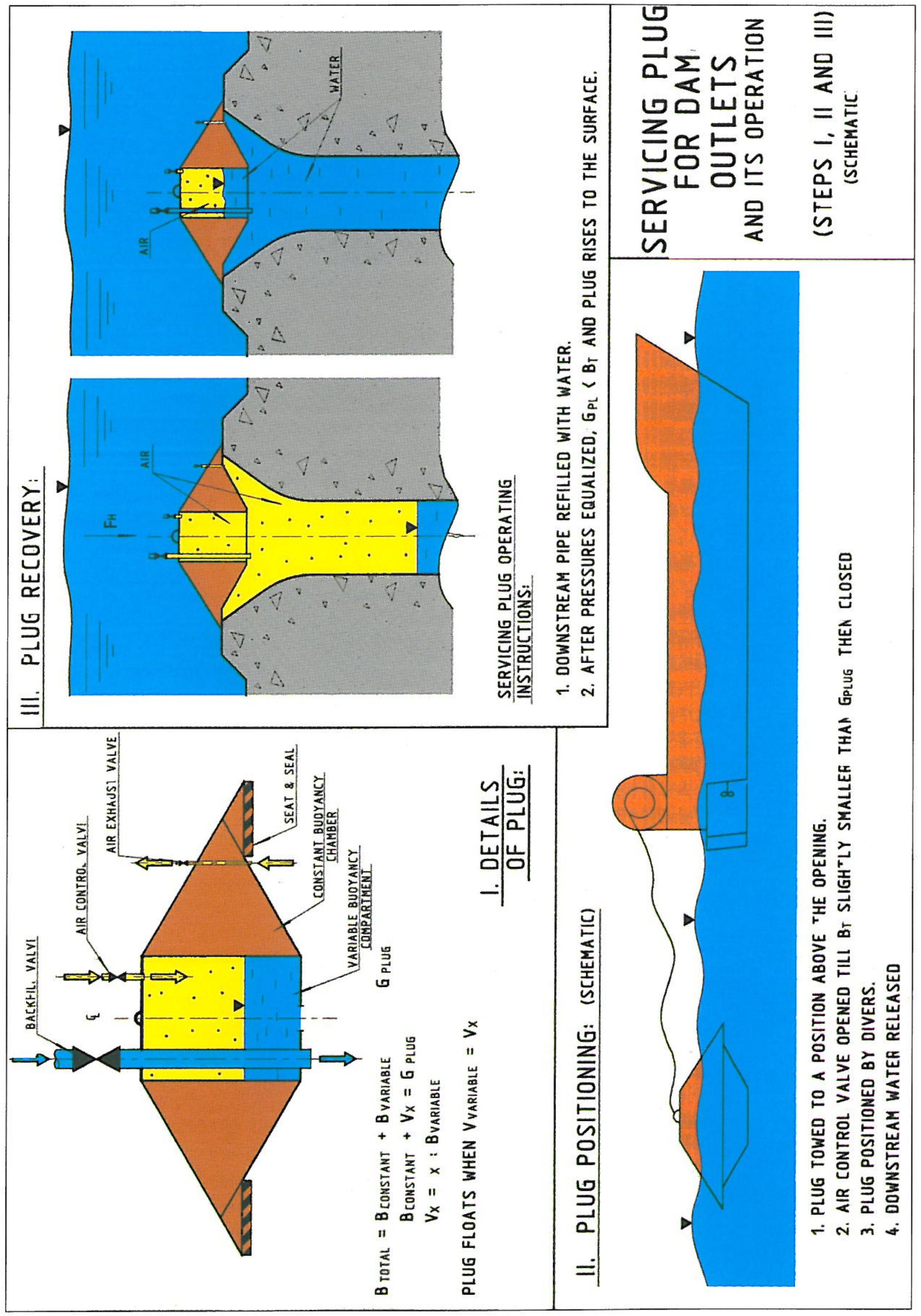


Figure 2: Servicing plugs and their installation and equipment

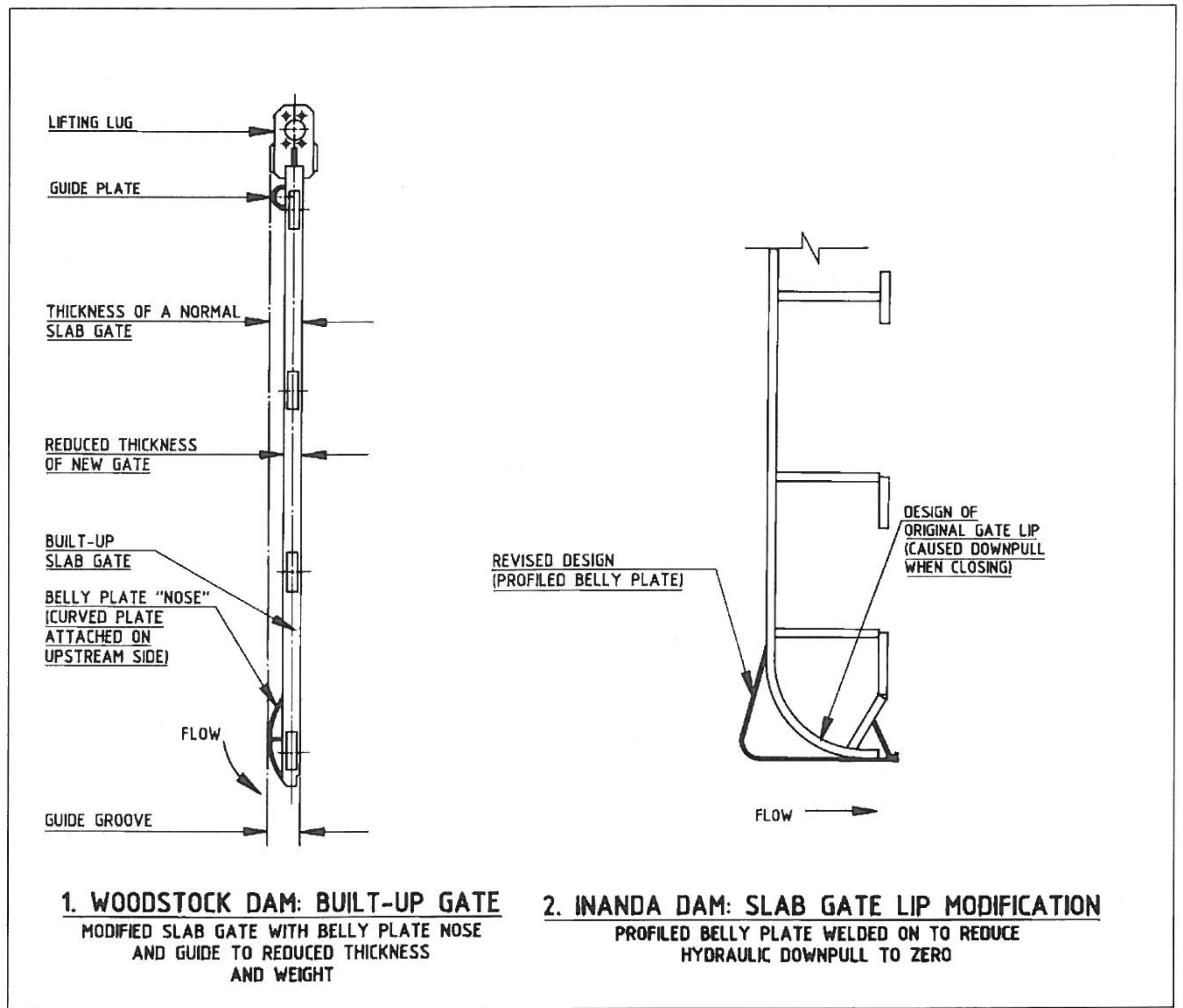


Figure 3: Improved slab gate designs to reduce weight and hydraulic downpull

paving blocks (Krugersdrif) for wave erosion control. A number of morning glory spillways exist (Ebenezer, Gubu, Zoeknog) and a fair number of syphon spillways (Bongolo, Mockes, Shongweni).

To deal with sediment, some dams are equipped with bypasses (Shongweni, Nagle) or with large gates (Welbedacht, Elandsdrift) or a hooded spillways section (Nooitgedacht). Off-channel storage dams (Knellpoort), however, so far seem to be the only effective way to deal with the silting-up of dams in South Africa.

FIVE INNOVATIONS IN MECHANICAL EQUIPMENT FOR DAMS DEVELOPED IN SOUTH AFRICA IN THE DEPARTMENT OF WATER AFFAIRS

1 The *in situ*-maintainable valve (ISM valve) *(Figure 1)*
2 Servicing plugs for dam outlets *(Figure 2)*
3 Slab gates for dams *(Figure 3)*
4 Pipe gates for raising full supply levels of dams *(Figure 4)*
5 Floating intake towers for optimal quality water draw-off *(Figure 5)*

1 ISM valve (*In situ*-maintainable valve)

This invention, developed in the Department of Water Affairs in 1990, provides an isolator installed in a pipeline upstream of a conventional valve or series of valves. This isolator valve remains open in normal day-to-day operation but it is brought into action quickly and simply when it is necessary to cut off the flow for emergency closure or for routine pipeline or valve maintenance. (Figure 1, p 228)

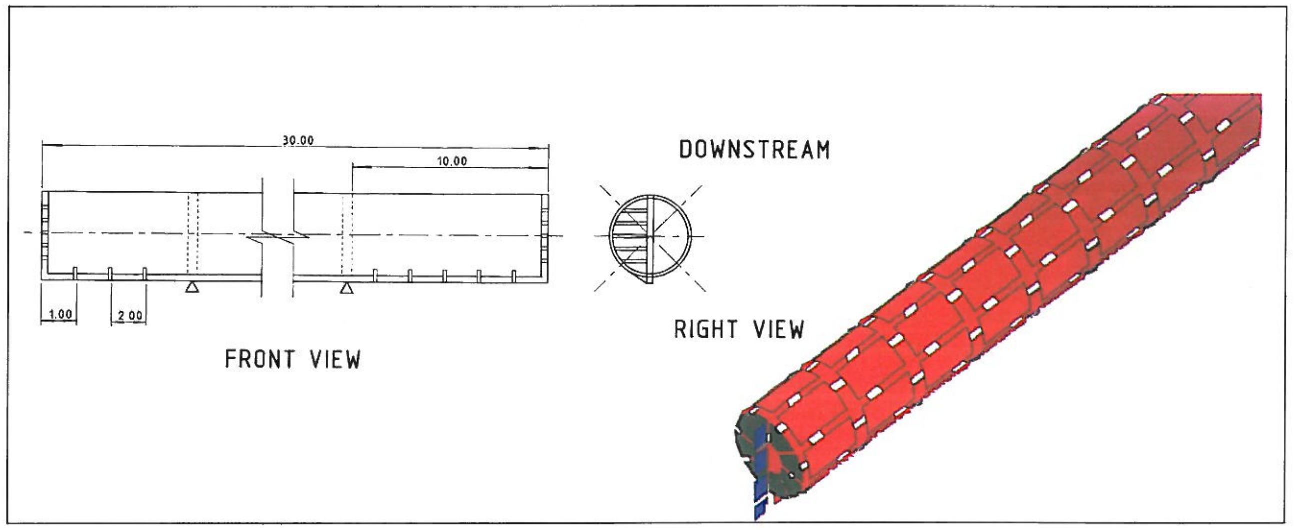


Figure 4: Pipe gate for raising full supply level and increasing capacity

The design ensures that isolation, when required, is immediate and effective and that there is no sticking or jamming of an inoperative isolator valve when emergency isolation is required. Following a successful emergency or planned maintenance operation, all seals, bolts, etc, on the isolator valve can be replaced in preparation for a subsequent maintenance exercise. The isolator valve may be operated electrically, hydraulically, pneumatically or manually. The isolator valve offers unrestricted and full bore flow through the pipeline (important for mines).

The size range envisaged is from DN 300 to DN 3 000 and the pressure range from 40 MPa to 0,25 MPa *(1 MPa = 10 bars)*. No upstream side gates, rails, hoists or cranes for sealing of the inlet are required when an ISM valve is to be installed.

2 Servicing plugs for dam outlets

The Mechanical/Electrical Engineering Directorate of the Department of Water Affairs has developed a number of different designs and shapes of plugs for servicing dam outlets. The equipment is used mainly for the maintenance of outlet pipelines. In principle they all consist of constant and variable compartments, seat/seal arrangement, air and back-fill valves and, if required, an air exhaust system.

Changing the buoyancy determines whether the plugs will float or sink. It is possible to make them weightless when submerged (mass about 10 tonnes). The hydrostatic reservoir pressure keeps them firmly seated above an opening ensuring watertight closure. The highest operating head to date has been 78 m on a 3 m diameter opening at the Hendrik Verwoerd Dam and the largest in size has been 5,4 m under a head of 30 m at the Floriskraal Dam. (Figure 2, p 229)

Plugs similar to these, sometimes in the form of concrete spheres, have been provided at the

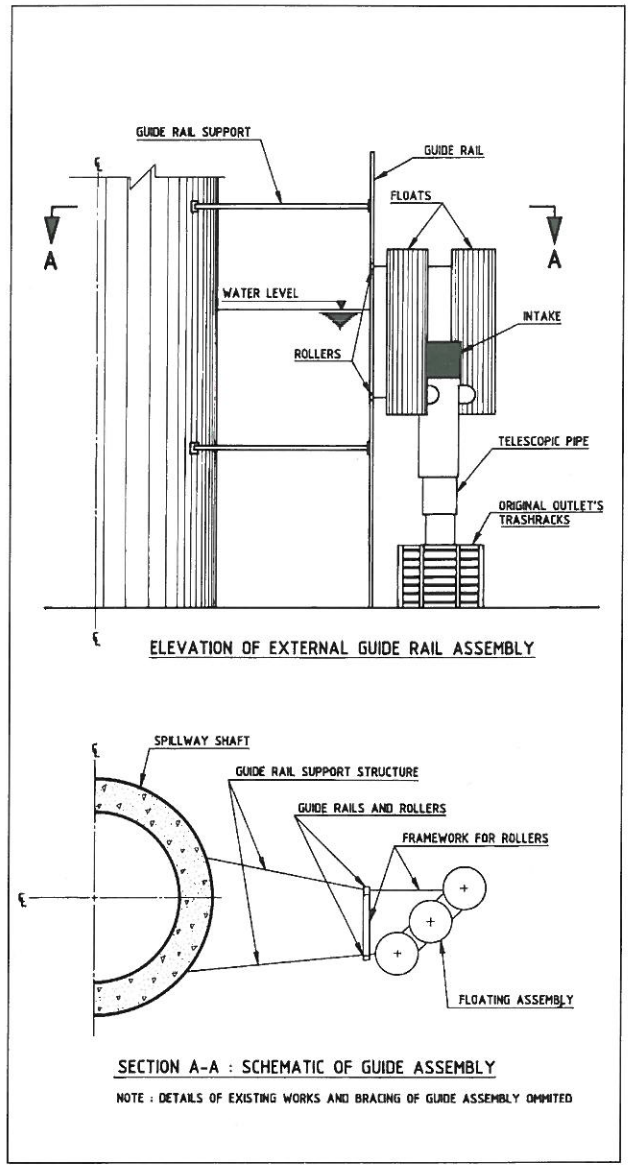


Figure 5: Floating intake tower for optimising draw-off level

Goedertrouw, Pongolapoort, Trichardtsfontein and Naute Dams (Namibia) and the Novo Pumping Station at the Knellpoort Dam, and have been successfully used.

3 Slab gates for dams

The slab gates of the Woodstock Dam, developed by the Department of Water Affairs in 1977, are superior in many respects to those of the Sterkfontein Dam, although they are for a lower head. Not only are they larger (controlling two openings of 2,45 x 4,37 m each, compared with 1,5 x 4 m at Sterkfontein Dam), but they are also fitted with pressurised rubber seals, making them positively watertight without increasing frictional forces (compared with the metal-to-metal sealing arrangement of the Sterkfontein Dam gates). They are furthermore equipped with a replaceable belly plate at the bottom edge. (Figure 3, p 230).

The bottom edge arrangement offers an easy repair possibility to the eroded gate's edge and since the slab is not any thicker, as determined by the edge geometry, the gate may be designed for strength only, thus becoming considerably lighter and cheaper. The Woodstock gates were designed by the Mechanical/Electrical Engineering Directorate and model tested in the Department's Hydraulics Laboratory. A further improved design was developed for the Inanda Dam. The belly-plate nose was enlarged and profiled to reduce hydraulic downpull to essentially zero.

4 Pipe gate for raising full supply level of dams (Bossiespruit)

To provide for maintenance of the aqueduct that supplies water to the Bossiespruit Dam from the Grootdraai Dam over a distance of more than 50 km, it was necessary to raise the dam wall to ensure a constant water supply to SASOL during the maintenance period. SASOL demands a daily average of 225 000 m^3 of water to function normally. A permanent raising of the wall could not be considered, owing to risk of failure in the high flood season.

A novel and cheap solution in the form of a pipe crest gate, designed by L Ruzicka of the Mechanical/Electrical Engineering Directorate of the Department of Water Affairs and manufactured by the central construction workshops of the Department, was developed and successfully tested at the dam on 6 October 1992. Water may now be stored at a higher level in September each year during the maintenance period. When not required, the pipe gate is raised above the crest by means of removable winches and the dam functions normally. The pipe gate consists of a mild steel 900 mm barrel, 30 m long, with a rubber seal mounted on a stiffener below the barrel. The two supporting columns, mounted on either side of the crest, were made of the same diameter barrel, which was cut to size and fitted with brackets for the winches. The columns were filled with reinforced concrete for added stability. The civil engineering work was performed by the Construction Directorate of the Department of Water Affairs. (Figure 4, p 231)

5 Floating intake tower for drawing off optimal quality water from a reservoir (Ebenezer Dam)

The purpose of this intake tower is to abstract the best quality water for purification purposes from a water reservoir irrespective of seasonal or long-term water level fluctuations. The best water is found normally in a layer of water several metres below the surface. Such a system has been implemented at the Ebenezer Dam and is described below.

The device comprises a telescopic inlet tower with its narrow end fixed to a dam outlet at the bottom and the top inlet end fixed to a float system, i.e. the telescopic shaft is suspended from a float resting on the water. The float may be raised or lowered, as required, by means of compressed air. The water level in a reservoir operates the system automatically. No sophisticated regulating equipment is required. The system is simple and effective. (Figure 5, p 231).

The floats follow the gradual vertical movements of the water surface automatically. No hoisting mechanisms, gate valves, computers, etc, are required as is the case with the more conventional systems. Floats consist of both variable and constant buoyancy tanks. The constant buoyancy tanks are filled with a polyurethane foam to make them unsinkable.

In the case of the Ebenezer Dam the telescopic shaft is guided by two columns that are anchored to the base platform situated 35 m below the full supply level and attached to the side of the morning glory spillway pier at the point above the maximum water level. The system was installed underwater at an existing dam under storage conditions with the help of divers.

SOME NOTES ON THE TECHNIQUE OF DAM BUILDING IN SOUTHERN AFRICA

Some six of the earliest dams built on the southern subcontinent of Africa in the period 1897 to 1910 for the city of Cape Town were of rubble masonry. In the period 1921 to 1952 a concrete arch-gravity dam was built there and raised twice. In the period 1957 to 1977 two further earthfill dams were built for greater Cape Town.

During the twenties and thirties dams built by the Irrigation Department were mainly concrete gravity spillways set in earth or rockfill embankments for broad sites, and single- or double-curvature arch dams with side-channel or chute spillways for canyon sites. Good examples of the latter are the Hartbeespoort, Paul Sauer and Pongolapoort Dams.

The technique further evolved to single and multiple double-curvature arch dams (also called cupola or dome types) as for example Kat River, Stompdrift and Wagendrift Dams. These were designed and analyzed by simplified arch analysis, later by structural models, and finally by finite-element numerical methods. Many of these dams are instrumented, and deflections, joint motion, stresses and strains are monitored.

Subsequent to a number of catastrophes in Europe involving arch dams (Vega de Tera, Malpasset and Vajont) and perhaps coinciding with the lack of suitable sites for arch dams, there was a move away from that type back to rockfill and earthfill dams (Hardap, Von Bach in Namibia and Sterkfontein in RSA). Some of these dams were equipped with shaft (morning glory) spillways (Ebenezer, Gubu and Zoeknog).

Three major dams of the thick double-curvature arch type were, however, still built in the seventies: Hendrik Verwoerd, PK le Roux and Naute (in Namibia), while some notable thin double-curvature arch dams were still constructed in the post-Malpasset era: Roode Elsberg, Hluhluwe and Craigie Burn Dams.

In the early eighties, subsequent to its use elsewhere in the world at Tarbela, Willow Creek and Monksville Dams, roller-compacted concrete (RCC) was increasingly employed in RSA dam-building practice, commencing with the De Mistkraal and Mokgoma Matlala Dams and culminating with Wolwedans Dam, the second arch-gravity RCC dam in South Africa.

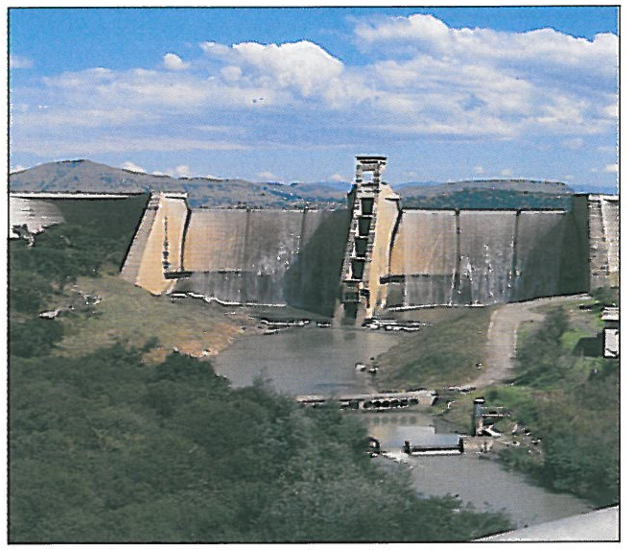
Other notable construction techniques, some less frequently employed, are:

- Rockfill with upstream concrete blanket (Ohrigstad Dam)
- Raising by post-stressed cables (Steenbras, Clanwilliam and Vaal Dams)
- Prepacked construction (Erfenis Dam) and low-sulphate cement (Beervlei Dam)
- Blast-furnace slag and fly-ash as cement extenders (most dams after 1950/70)
- Pre-cooling by ice (Pongolapoort Dam)
- Dressed-stone masonry (Woodhead, Hely Hutchinson and Bulshoek Dams).

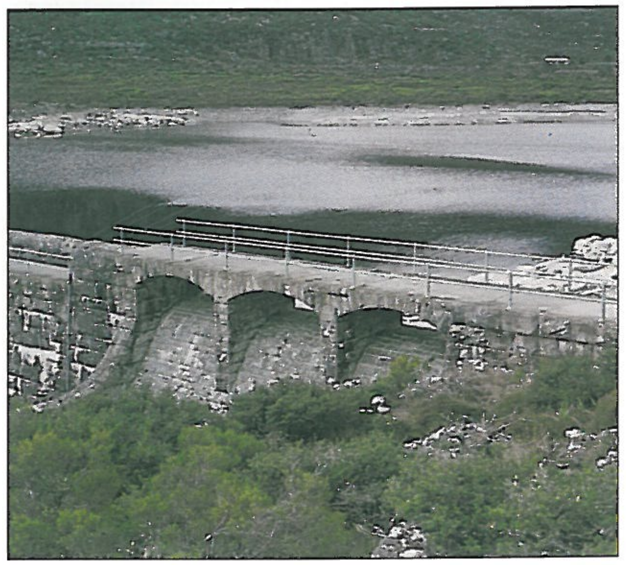
The 113 m^3/s Vanderkloof main canal during construction, Orange River Project (Photo JM Jordaan, Jr)

HISTORICAL SEQUENCE BY TYPE OF DAM (names of dams in italics*)

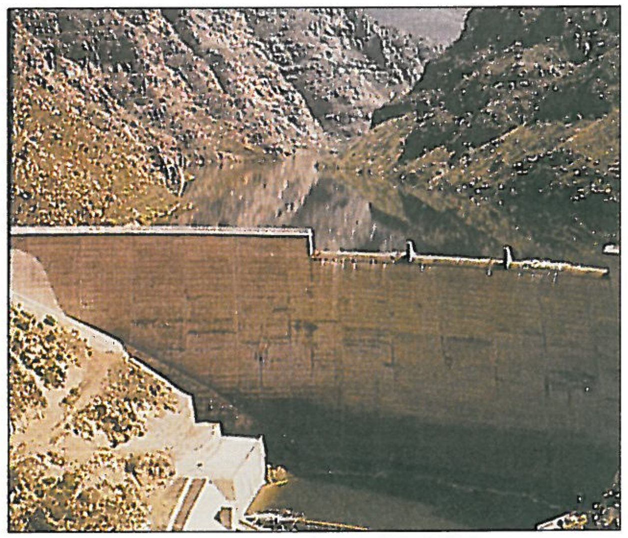
1. *Waegenaars*, the first dam and reservoir in South Africa, was built in 1663.
2. *Woodhead* (1897): First stonemasonry dam in the country.
3. *Bongolo* (1908): First syphon-spillway dam in the country.
4. *Smartt* (1912): First earth embankment to be washed away in South Africa.
5. *Vaal Barrage* (1921): First dam for the Rand Water Board (Rand Water).



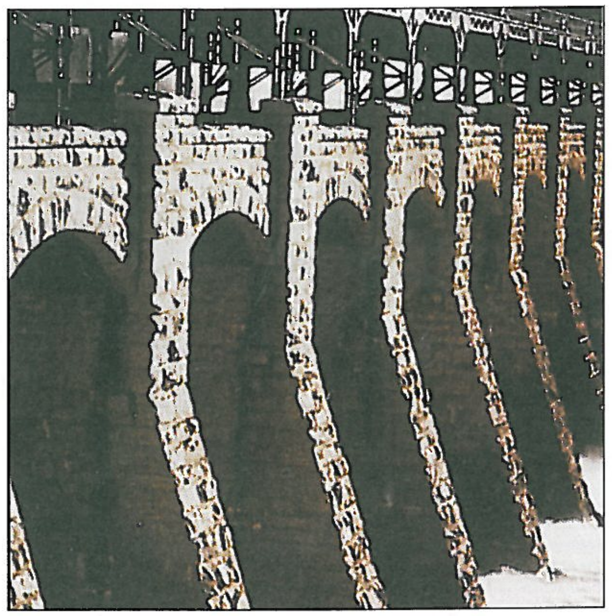
Wagendrift Dam



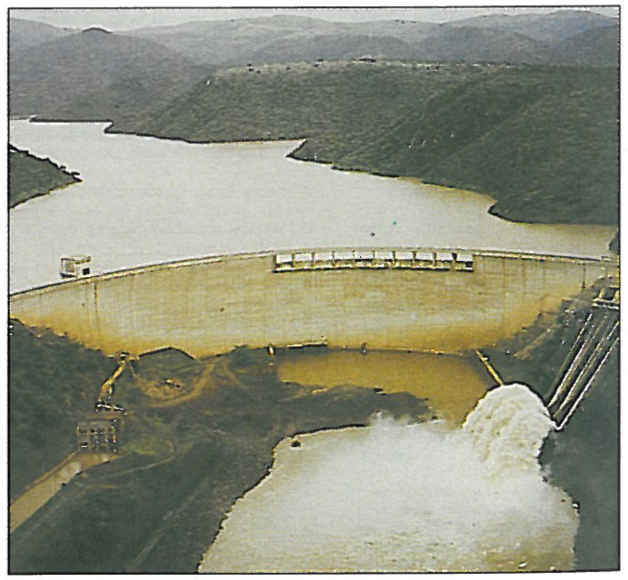
Woodhead Dam spillway



Roode Elsberg Dam

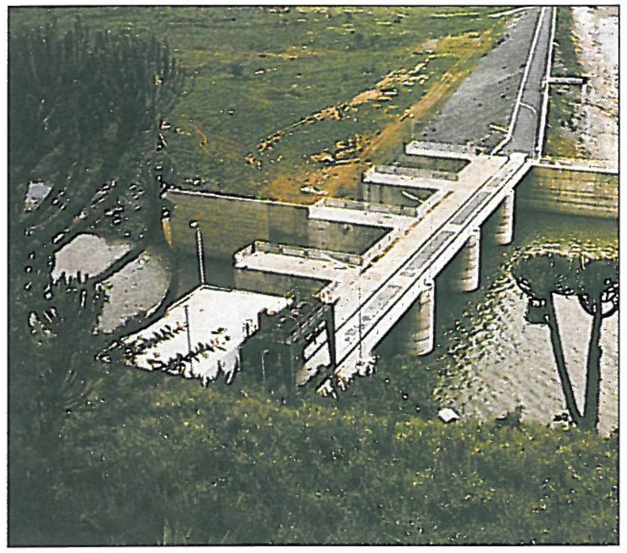


Bulshoek Dam



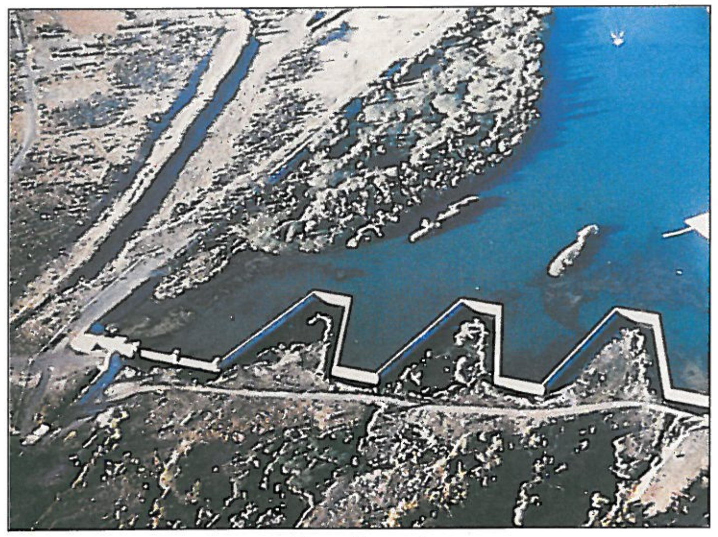
Pongolapoort Dam

Kat River Dam



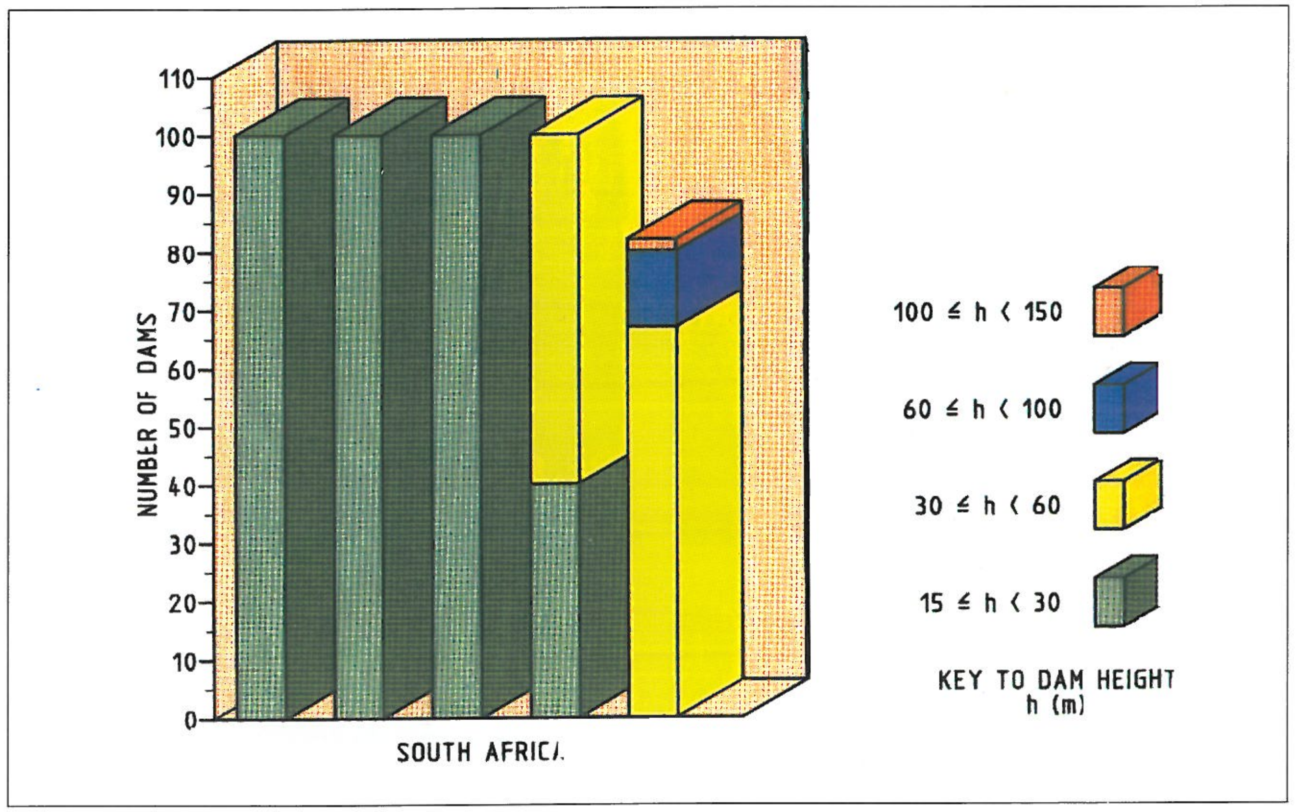
Elandsdrift Barrage

6. *Steenbras* (1921): Post-stressing with cables was first used when the dam wall was raised in 1954.
7. *Bulshoek* (1923): Stonemasonry and gravity dam. First agricultural dam in the country.
8. *Buchuberg* (1931): First dam on the Orange River.
9. *Vaal Dam* (1938): Strategically most important dam in the country.
10. *Nooitgedacht* (1962): First duckbill-trough spillway in South Africa.
11. *Wagendrift* (1963) and Stompdrift (1965): First multiple dome dams in the country. Wagendrift is also reinforced.
12. *Craigie Burn* (1965): First thin shell dome dam in the country.
13. *Paul Sauer* (1964) and *Pongolapoort* (1972): First double-curvature single-arch dams in the country.
14. *Roode Elsberg* (1968): Largest thin-shell arch dam in the country.
15. *Hendrik Verwoerd* (1972): Largest reservoir capacity of all dams in the country.
16. *Sterkfontein* (1977): Largest earth-fill dam in the country.
17. *P.K. le Roux* (1977): Highest double-curvature arch dam in the country.
18. *Grootdraai* (1982): First dam used in a reverse-flow augmentation scheme.
19. *Knellpoort* (1988): First rollcrete arch-gravity dam in the world.
20. *Inanda* (1989): Latest component in the Mgeni River System (Umgeni Water).
21. *Wolwedans* (1989) Largest rollcrete arch-gravity dam in the country.

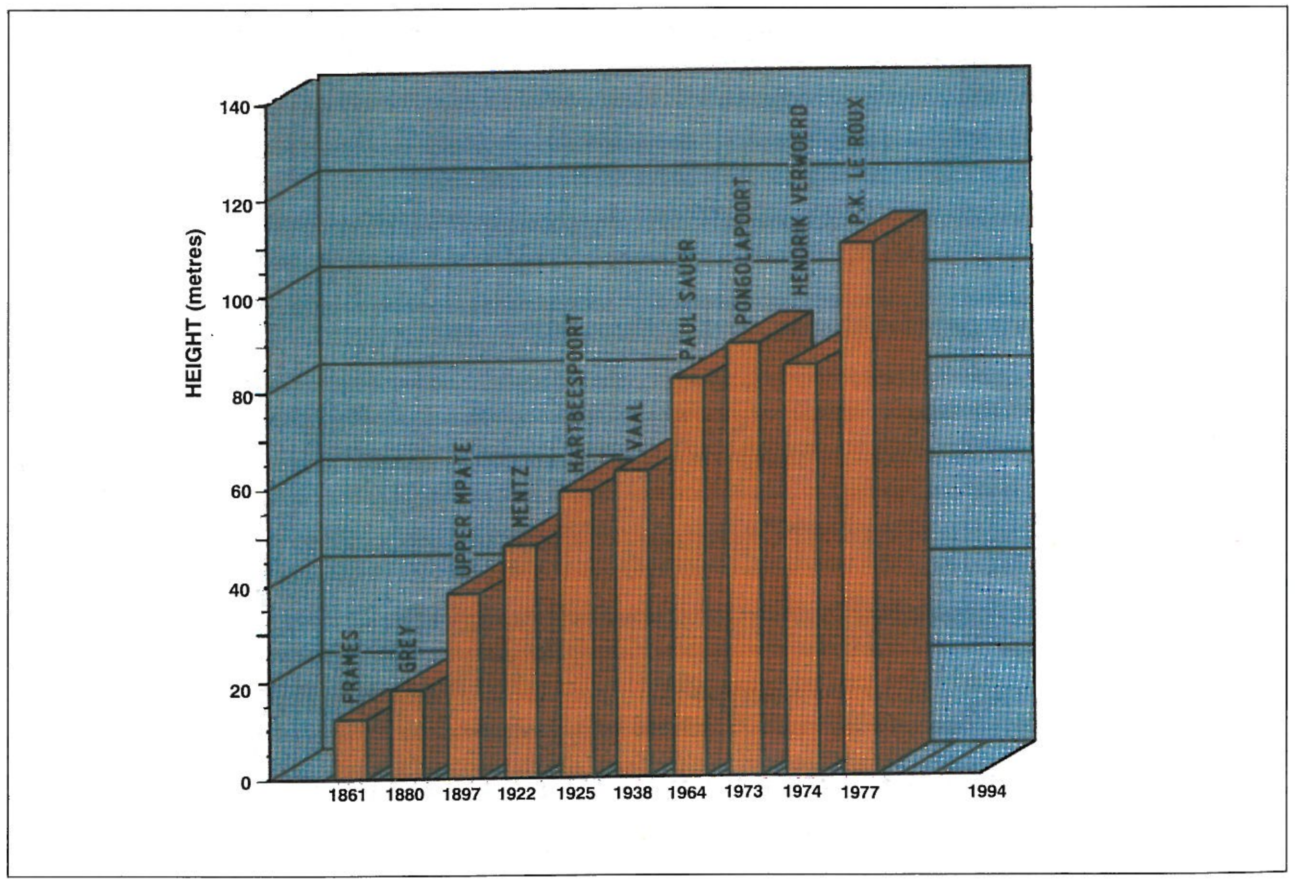


Douglas weir

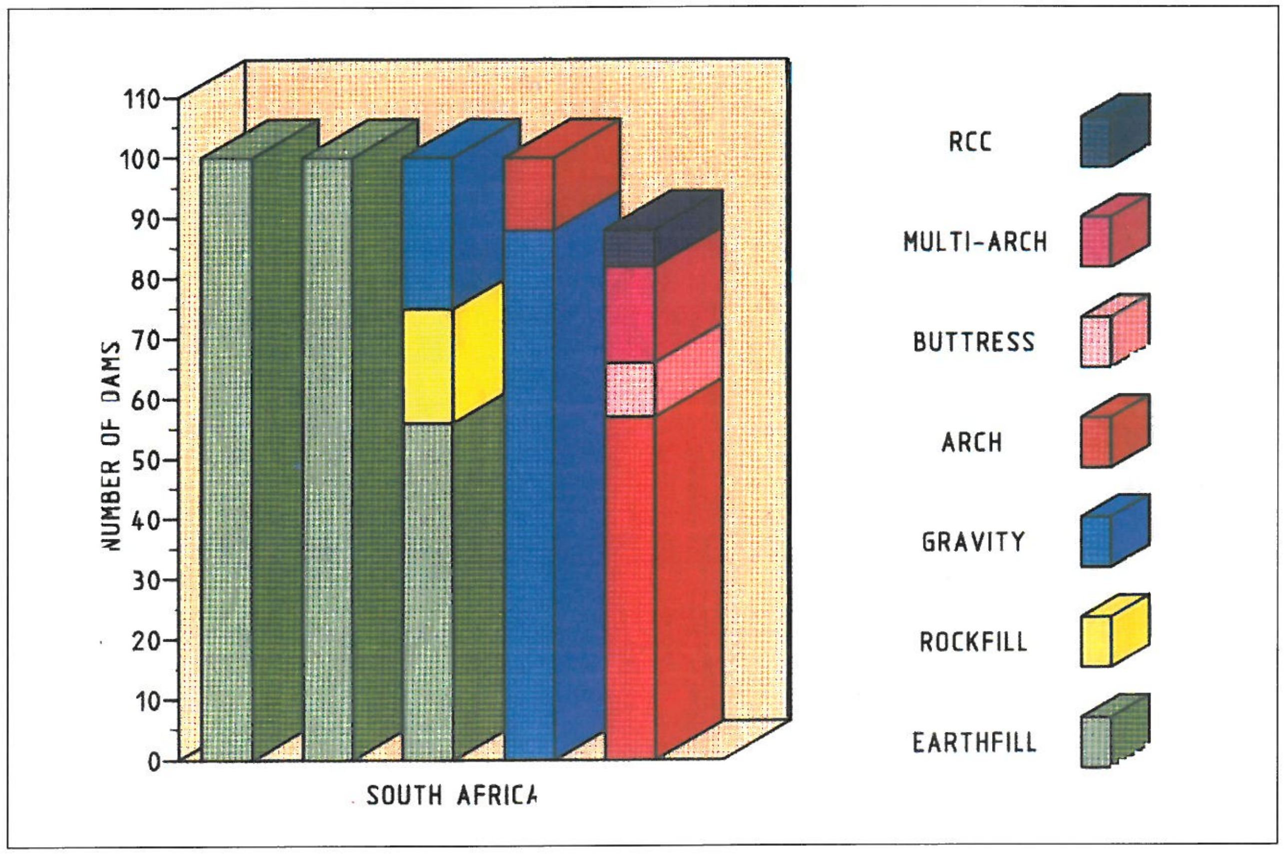
**Note: A portfolio of photos, not related to the historical sequence, illustrating variety in styles*



South African large dams: Classified by ***height*** *(Intl. Water Power and Dam Construction 1990 — Handbook)*



Landmark dams of South Africa: Development in height since 1860



South African large dams: Classified by ***type*** *(Intl. Water Power and Dam Construction 1990 — Handbook)*

REFERENCES

ESKOM. (No date) *Annual Reports*

International Water Power and Dam Construction, Yearbook (1991)

International Commission on Large Dams (1988). *"1st updating" World Register of Dams.*

Jordaan JM (Sr) (1950). *Water control and utilization in the USA,* Government Printer, Pretoria

Jordaan JM (Sr) (1969). *Dams and water conservation in the Republic of South Africa.* Paper presented at the Civil Engineering Department, University of Delaware, Newark Delaware, USA. July 1969

Jordaan JM (Jr) (1973). *Operating rules for flood control by reservoirs.* Proc Eleventh Congress on Large Dams: 203-215 Madrid, Spain

Kovacs ZP, Roberts CPR and Jordaan JM (Jr) (1984). *Overtopping of dams by surging flow.* The Civil Engineer in South Africa, vol 26(8): 383-389

Merensky K and Hopkins D (1979). *Automatic water-level control in South Africa.* Journal of the Hydraulics Division, Am Soc Civ Eng, vol 105 (HY11): 1415-32

Nicol SM (1973). *Efficient flood control of dams equipped with crest gates.* ICOLD. Proc Eleventh Congress on Large Dams: 186-189. Madrid, Spain

Olivier H (1975). *Damit.* MacMillan

Olivier H (1977). *Great dams in Southern Africa.* Purnell

Rand Water. (No date) *Annual Reports*

South Africa, Department of Water Affairs (1983). *Guidelines relating to the control of dams equipped with crest gates.* Unpublished internal report. Pretoria

South Africa, Department of Water Affairs (1987). *South African dams.* Government Printer, Pretoria

Umgeni Water. (No date) *Annual Reports*