EXECUTIVE SUMMARY

South Africa has several inter basin water transfer schemes, as indicated in Figure 1-1, with the most recent one the Lesotho Highlands Water project (LHWP) transfer tunnels bringing water under gravity from Lesotho through about 80 km of concrete lined tunnels. South Africa also has the largest irrigation tunnel in the world, the 5.33 m diameter Orange-Fish Tunnel, 81 km in length.

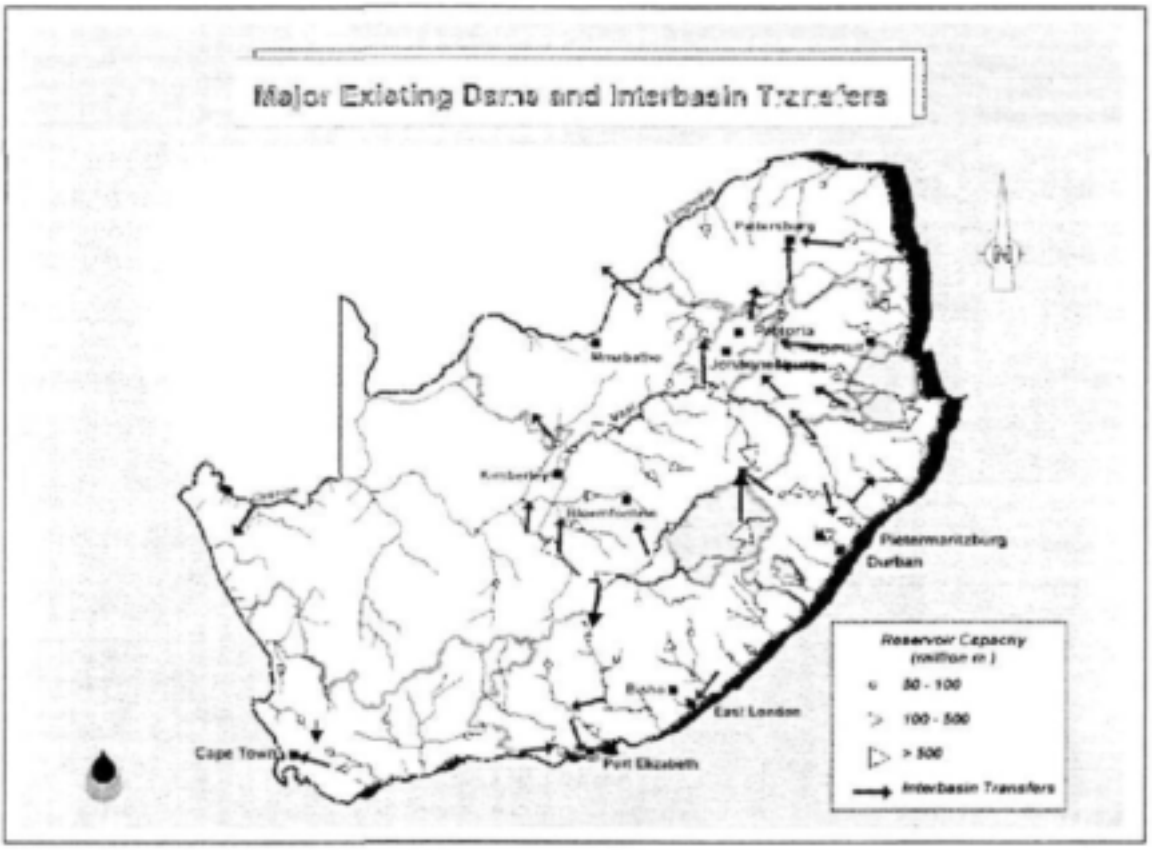

Figure 1-1 Water transfer schemes in South Africa

A concrete lined tunnel can lose as much as 30 percent of its hydraulic capacity over a period of 30 years. Engineers have a sound knowledge of the hydraulic roughness of new tunnels, as has been confirmed during the recent (1998) commissioning tests of the LHWP Transfer and Delivery Tunnels. Furthermore, recently completed research funded by the Water Research Commission (Pegram and Pennington, 1998) helps to assess the hydraulic capacity of new tunnels. There is however a need for a better understanding of the tunnel ageing process in order to plan for the phasing in of future possible new tunnels as water demands increase.

South Africa will have to rely more and more in future on water transfer schemes. These tunnels are extremely expensive, with estimated capital costs of about R30 000 /m length.

The main aim of the project was to provide a reliable hydraulically based methodology with which concrete lined tunnel ageing and the associated decrease in hydraulic capacity can be predicted. Both the ageing mechanisms of sliming (with sediment deposition) and soft water corrosive conditions were investigated. This will ensure the timeous phasing in of new schemes when tunnel ageing decreases the hydraulic capacity.

Furthermore, the aim was to establish whether remedial measures can be implemented to reverse or contain the tunnel ageing process.

Tunnel design and operation guidelines were also developed to limit tunnel ageing.

This study combined laboratory and field test data to obtain a better understanding of the ageing process in large diameter conduits such as water transfer tunnels. Field tests were carried out since 1998 at the Orange-Fish Tunnel, Roode Elsberg Tunnel and Theewaterskloof Tunnel, while laboratory investigations at the Universities of Stellenbosch and of Pretoria were also carried out on pipes. The following are key findings of this research project:

- Hydraulic ageing is caused by sediment deposition consisting of fine cohesive sediment, in some cases also containing some organic material. Manganese deposition by bacterial action also occur which is difficult to flush out at high discharge. In the Theewaterskloof Tunnel, sand at the tunnel invert also deposited due to diversion of Berg River water into the tunnel.

- Soft water corrosion occurred at the Western Cape and LHWP tunnels. The effect is a softening of the upper 3 mm of concrete, but this was protected by a thin layer of sediment at all the tunnels investigated. The soft water corrosion can however lead to deep scour holes and etch marks in the concrete, where a poor quality concrete was used during construction (Theewaterskloof Tunnel). This is however not expected in the high strength LHWP concrete lining.

- A relationship was developed and calibrated to determine the effective hydraulic roughness of a segmentally lined tunnel, including the joint step losses.

- A hydraulic rate of ageing equation was developed and calibrated on UK and South African data, for conditions where sediment deposition and sliming plays a role. The pH of the water is a dominant variable.

- An ultimate hydraulic roughness equation was developed and calibrated. A probable and maximum probable ultimate roughness formulation have been proposed.

- Hydraulic flushing at high flows are effective in reducing the hydraulic roughness by flushing out sediment deposits from the tunnel. Where bacterial action however plays a role, one cannot rely on flushing alone and other measures have to be considered.

- Chlorination has been used at a limited scale elsewhere in the world to reduce roughness, but was found more effective after cleaning of the tunnel. Depending on the system configuration, there are environmental problems associated with chlorination.

- Mechanical cleaning of a tunnel in soft water conditions is not recommended since it damages the tunnel and increase the roughness, no matter how careful you are. In hard water conditions, high pressure water jets damaged the tunnel surface. Literature also indicates rapid increase in roughness after cleaning, within one to two years.

- Tunnel linings such as poly-urethane can be considered in conditions of soft water corrosion, but should preferably be applied during the tunnel construction. These linings are however expensive and their lifespan is unknown. A good quality concrete without a lining, designed and operated correctly, should be sufficient for most conditions.

- Literature reviewed indicates that there are two main factors influencing the deterioration of the concrete due to soft water attack, namely the aggressiveness of the water and the composition of the concrete under attack.

No cement extenders were used in the concrete of the Theewaterskloof Tunnel and it was found that the leaching rate of Ca-ions increase exponentially with an increase in the water operating velocity in the pipe system. The main chemical process taking place in the concrete during soft water attack in the Theewaterskloof Tunnel is the *leaching of $Ca(OH)_2$. A maximum and minimum theoretical concrete deterioration* depth rate was determined for the concrete. These rates also increase exponentially with an increase with water operating velocity in the pipe system. The permeability of this concrete is very high and therefore the leaching rates are also high.

The concrete mixture of the LHWP linings of the delivery tunnels contains fly-ash as a cement extender. Two different Ca-ion leaching rates for a specific water operating velocity were found for the LHWP concrete. It indicates that as a result of the fly-ash content in the mixture, decalcification of the C-S-H gel takes place at a low rate and $Ca(OH)_2$ leaching at a higher rate. The theoretical concrete deterioration depth rates for the LHWP concrete are much lower than the rates for the Theewaterskloof Tunnel. There are not enough data available at this stage, but it seems that the concrete deterioration rate increases with an increase of water operating velocity.

Although the soft water attack cannot be stopped with a specific concrete mix design it is possible to decrease it significantly with an optimum design. The optimum concrete mixture as designed by Castro & McIntosh (1994) for the LHWP tunnels will still be the best mixture for resistance to soft water attack because the $Ca(OH)_2$ content is very low in this design mix.

- Design and operational guidelines for the determination of tunnel ageing and selection of tunnel diameter during design, have been proposed. The LHWP Delivery Tunnel North (DTN) has been used as a case study.
- Prediction of future ageing of the LHWP DTN indicates that under current operating conditions, the rate of ageing would be relatively small and the ultimate discharge capacity would be between 80% to 85% of the new tunnel capacity. Previous studies used a higher ultimate roughness (DWAF, 1999) of k_s = 4 mm which resulted in an aged discharge capacity of about 73% of the original capacity. The current predictions therefore indicate that it might be possible to implement the next phase of the LHWP without doubling the tunnels: Low Mashai Dam, that would require a total tunnel discharge capacity (including phase I flow) of 35,8 m^3/s without downtime, or 39,8 m^3/s with 10% downtime.

It is recommended that the design guidelines (Chapter 10) are followed during the design of a tunnel. Even more important however, is that the tunnel should be operated according to the design.

- Regular hydraulic tests at say 5 year intervals should be carried out at the LHWP, Theewaterskloof, Orange-Fish and Roode Elsberg Tunnels to determine the hydraulic roughness to extend the current data base.
- The theory developed for this study should be calibrated against field data of pipelines for application in pipe design.

Attention to the following chemical aspects regarding soft water corrosion is necessary:

- More laboratory tests are necessary on the LHWP test section at higher water operating velocities to determine the relationship between the Ca-ions leaching rates and water operating velocities.

- Tests on the microstructure of the concrete of the test sections are necessary to calibrate the rate of the theoretical concrete deterioration depths and to determine the exact influence of the permeability and porosity on soft water attack.
- Tests on the Theewaterskloof Tunnel core have to be completed to calibrate laboratory tests.
- A core from LHWP is required to calibrate laboratory tests.
- The aggressiveness of the water actually flowing through the tunnels should be determined. Laboratory tests with the water from the field will be necessary to confirm the calibration of the accelerated rate of deterioration in the laboratory with the actual field behaviour.
- Further tests on concrete mixtures with silica-fume as cement extender will be valuable to determine a concrete mixture with a higher resistance to soft water attack.
- The effect of soft water in the concrete mix should be studied
- Coatings should be applied in the Delivery Tunnel North to evaluate its long term performance
- Tunnels should not be cleaned by mechanical equipment or water jets, as this will increase the hydraulic roughness, especially in softwater conditions. Controlled hydraulic flushing at high discharge is recommended instead.