A geographic information systems analysis of hydro power potential in South Africa

A. Ballance, D. Stephenson, R. A. Chapman and J. Muller

ABSTRACT

Electrification can reduce the dependence on combustible fuels and therefore also reduce the concomitant health risks. Hydro power is one possible method of generating electric power close to the potential consumers, thereby cutting out expensive reticulation costs in widely spread rural areas. For sustainable electricity generation there must be stream flows of sufficient flow rates down significant slopes.

A preliminary assessment of hydro power potential in South Africa was undertaken by estimating actual energy potential calculated from digital maps of slope and runoff. Coefficients of variation and low flow indices proved good potential measures of flow variability and risk. The methodology allowed rapid identification of micro- and macro-hydro power potential. Micro-hydro power potential identification was calculated from run of river and local flow, while macro-hydro power generation needs storage and thus cumulative river flows were used. The steeper and more humid slopes of the eastern escarpment, and parts of the southern escarpment near Cape Town, showed the best potential for both micro- and macro-hydro power (with annual energy potential values in excess of 10^7 kWh yr^{-1} and 10^9 kWh yr^{-1}, respectively). This preliminary assessment was intended to lead to further more detailed and in-field assessments of hydro power generating capacity.

Key words | macro-hydro power, micro-hydro power, GIS, potential

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INTRODUCTION

Communities without a centralised electricity supply are more dependent on the natural resource base for fuel for cooking, lighting and heating. Communities that do not have access to electricity burn gas, paraffin, dung, crop residues, coal, wood, and even refuse (Viljoen 1992). There are significant health risks associated with burning these fuels, notably respiratory illnesses, cancer, and carbon monoxide poisoning (Smith 1987; Pondey 1989; Von Shirnding & Kleine 1991; Terblanche *et al.* 1992). Toxicity is a result of incomplete combustion, poor ventilation, open flames and low levels of technology. Approximately 24 million people are exposed to hazardous levels of air pollution as a result of using wood and coal as household energy sources (Terblanche & Golding 1994). Children in electrified homes, however, are at less risk of developing respiratory illnesses than children who live in unelectrified homes, both urban and rural (Terblanche & Golding 1994).

In rural areas increased use of wood for fuel contributes to deforestation, degradation of woodlands and changes in biodiversity and species competition (e.g. Griffin *et al.* 1993; Shackleton 1993; Banks *et al.* 1996).

Electrification is a solution to indoor air pollution and the associated health risks, as well as providing social upliftment, and conservation of certain natural resources. At the end of 1996, 45% of South African households (73% of rural households and 21% of urban households) had no electricity supply, despite 1.4 million new connections between 1994 and 1996 (South African Institute of Race Relations 1998).

Hydro power is being considered as one of the options for generating power for rural communities, as it is less damaging environmentally. Hydro power is sustainable in that water is a renewable resource, and there are no emissions or effluents associated with hydro power generation. For micro-hydro power, diversion and damming of rivers may not be necessary; therefore there are few, if any, of the environmental impacts associated with large dams. Damage to fish in turbines is thus reduced, and barriers to migration of aquatic organisms are less significant than those caused by macro-hydro power generation (Kubečka *et al.* 1997). Provision of electricity through installation of micro-hydro power generators to communities currently dependent on wood for fuel will reduce the collection pressure on woody biomass.

There is no clear consensus regarding the classification of scales of hydro-electro power. However, a small hydro plant could be less than 10 MW, a mini plant is generally less than 1 MW, and a micro plant is generally less than 100 kW. (The latter figure would be sufficient typically for 100 rural huts and a community centre, based on 1 kW per hut and a typical diversity factor.)

Apart from the scale of development, the philosophies behind macro-hydro power and micro-hydro power are different. Macro-hydro plants (small and large) are generally designed to connect into a bigger grid. They can be employed to generate during peaks in the electrical consumption, thereby exploiting the economic benefits of scale. This concept is taken further in the case of pumped storage where there is a net loss of energy. The economic advantage is the low cost of the turbines compared with thermal sourced machines. In 1994 hydroelectric power comprised only 1.7% of the installed electricity generating capacity in South Africa (total 40,000 MW) (Scholes *et al*. 1994) and 90% of the hydro power plants are classified as macro (Stephenson 1997).

The costs of civil works (dams, penstocks, power stations) can be relatively high in a macro-hydro-electric installation and these costs cannot necessarily be scaled down proportionally to smaller stations. Therefore the total project cost per kW installed may be higher for mini-hydro and micro-hydro stations. (Construction costs are typically in excess of R10,000 per kW of output.) The advantages of micro plants manifest particularly in the saving in transmission network for remote users, as the typical micro-hydro plant is designed just to serve a local community; thus long, high voltage lines and associated energy losses are avoided.

Other infrastructure development costs can sometimes be ameliorated on micro schemes. Seasonal dam storage costs can be avoided if the required flow is less than the low river flow. If the water source does dry up, an alternative power source would be necessary. Flood spillway costs can be avoided if the power station flow is diverted off the main channel to a gorge or ravine. Sealed turbine units may obviate the necessity of power stations. Low set efficiencies may be tolerable if there is surplus river flow. Transformer costs can be reduced by reticulating at low voltage, which also enhances safety.

Micro-hydro power therefore has some distinct advantages over macro-hydro power. Some of the hydraulic problems associated with small hydro developments were discussed by Stephenson (1999). In this paper we describe our search for both macro- and micro-hydro power sites in South Africa using a Geographic Information System (GIS) and some statistics.

METHODOLOGY

Two models were developed in this study. The first was developed to determine areas suitable for micro-hydro power potential, for which small dams or barrages would be required. The second was developed to identify areas for macro-hydro power, via damming of rivers and construction of large output turbines. For the purposes of providing power to areas of the country currently not connected to the national grid, it is expected that micro-hydro power is the preferable option. Furthermore, most of the major rivers in South Africa are already dammed or modified, although macro-hydro power generation contributes an insignificant fraction of the national energy production.

The first part of our approach was to look for steep gradients using GIS analysis. A digital map of point heights at 400 m intervals (Surveyor General 1996) was used to derive a slope map for the country by analysing the height difference between points. An intrinsic GIS function was used to do this, and areas between points were converted to cells, resulting in a map of cells, each with a slope value assigned to it.

The next step was to calculate flow rates for each cell. Modelled monthly and mean annual runoff (MAR) data have been developed for all fourth order (quaternary) catchments in South Africa (Water Research Commission 1996). Each runoff data set is associated with a map of the catchment boundary. A union of the slope map and the catchment boundary map was then created, each cell within the catchment boundary being assigned the mean annual runoff depth for that catchment (calculated by dividing the MAR volume by the catchment area). All cells within the catchment boundary therefore have the same runoff value.

Mean annual flow volumes (MAFV) for each cell were then calculated by multiplying cell area by the mean annual runoff depth.

Micro-hydro power potential

The approach adopted was to look for the combination of sustainable high flow rates and steep gradients with which to create the necessary head for micro-hydro power generation. The low flow characteristics of the river or stream were also investigated to ensure sites had reliable dry season flows, in order to provide power all year round.

The next step was to calculate energy potential, using Equation (1). In engineering designs, flow values are often determined per 1,000 m of river reach. As the data had been supplied at 400 m intervals, it was re-sampled to 1,000 m intervals using inherent GIS functions:

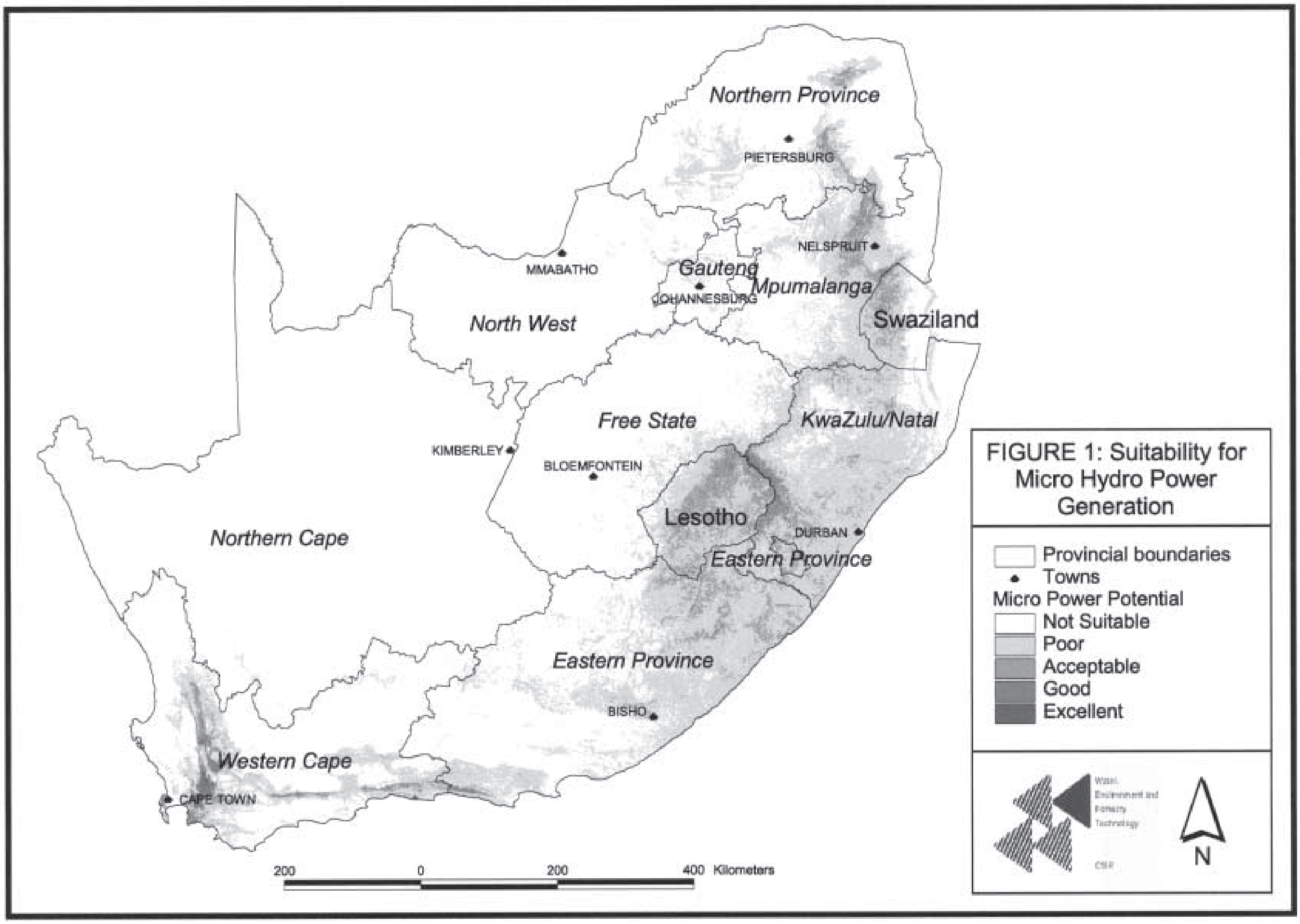
$$\mathrm{AEPL}\ (\mathrm{kWh\ yr^{-1}}) = 9.8\ (\mathrm{m\ s^{-2}}) \times \tan(\Theta) \times \mathrm{Reach} \times \mathrm{MAFV}\ (\mathrm{m^3})/3{,}600\ (\mathrm{s}) \quad (1)$$

where: AEPL = Local Annual Energy Potential, in kilowatt hours per year
9.8 = acceleration due to gravity, in metres per second squared
Θ = river gradient in radians
Reach = river reach length (1,000 m)
MAFV = mean annual flow volume per km^2 of catchment, in metres cubed
3,600 = the number of seconds per hour.

The calculation of micro-hydro energy potential uses MAFV per unit area, rather than cumulative flow. With the aim of supplying rural communities with reliable power from micro-hydro, the total volume of river flow was thought not to be as important as the convenience of a local power source. The proximity of fast flowing water, even if not at a great flow rate, could enable local micro-scale generation to be exploited. For example, at the source of a river (high in the mountains) there is relatively less volume of water, but the steep gradient provided by the mountains results in a higher potential for power generation, because of the energy of the falling water.

Micro-hydro power, which is dependent on instantaneous stream flow, is susceptible to variation in flow. South African rivers are well known for their highly variable flow. The generating capacity of a run-of-river micro-hydro operation would be constrained by low flow conditions. A measure of flow variation and low flow values were therefore included in this assessment of micro-hydro suitability.

Midgely *et al.* (1994) have simulated 72 years of monthly runoff from each of the fourth order catchments. A low flow index (LFI) and coefficient of variation (COV) in mean annual flow were calculated from these data. The COV is a measure of frequency of low flow, calculated from the annual total flows. The LFI is a measure of the severity of low flows, calculated as the mean of the values for the lowest one, two, and three month flows, expressed as a percentage of the MAR. Together, these give an indication of the risk of failure (i.e. insufficient water in some years to operate the design capacity and the relative catchment storage required to carry over from wet to dry season). Results of these calculations were mapped using GIS to aid selection of areas for further investigation. However, Midgely *et al.* (1994) calculated COV and LFI values per fourth order catchment, and more detailed simulations would be required to develop a single index of micro-hydro power suitability, incorporating risk of low flow.



Macro-hydro power potential

Macro-hydro sites are different in that they require characteristics suitable for the damming of rivers and large storage volumes. A river increases in flow rate as it proceeds down a catchment, as a result of increasing catchment area and the accumulation of its runoff. However, the river gradient usually decreases in the lower parts of the catchment; hence the specific energy in the river is less. These areas are more suitable for macro-hydro power because dams can provide the required head and sufficient storage of water in large reservoir basins to supplement water requirements during times of low flow, ensuring year-round power generation. The approach taken was therefore to identify areas of large cumulative flow.

A cumulative mean annual flow volume (CMAFV) was calculated by aggregating the mean annual flow volumes of all cells up-stream to any given cell along simulated river channels. These channels were developed by overlaying altitude, gradient and slope direction, and synthesising a flow direction for each cell (i.e. determining whether a cell has a net inflow or outflow of water). Sequences of cells with high cumulative flow volumes were considered analogous to rivers.

This technique was validated by comparing maps of these simulated river channels with mapped rivers from the Surveyor General. In some cases these computed cumulative flow sequences terminated where a cell had an unusually high or low altitude value, producing an

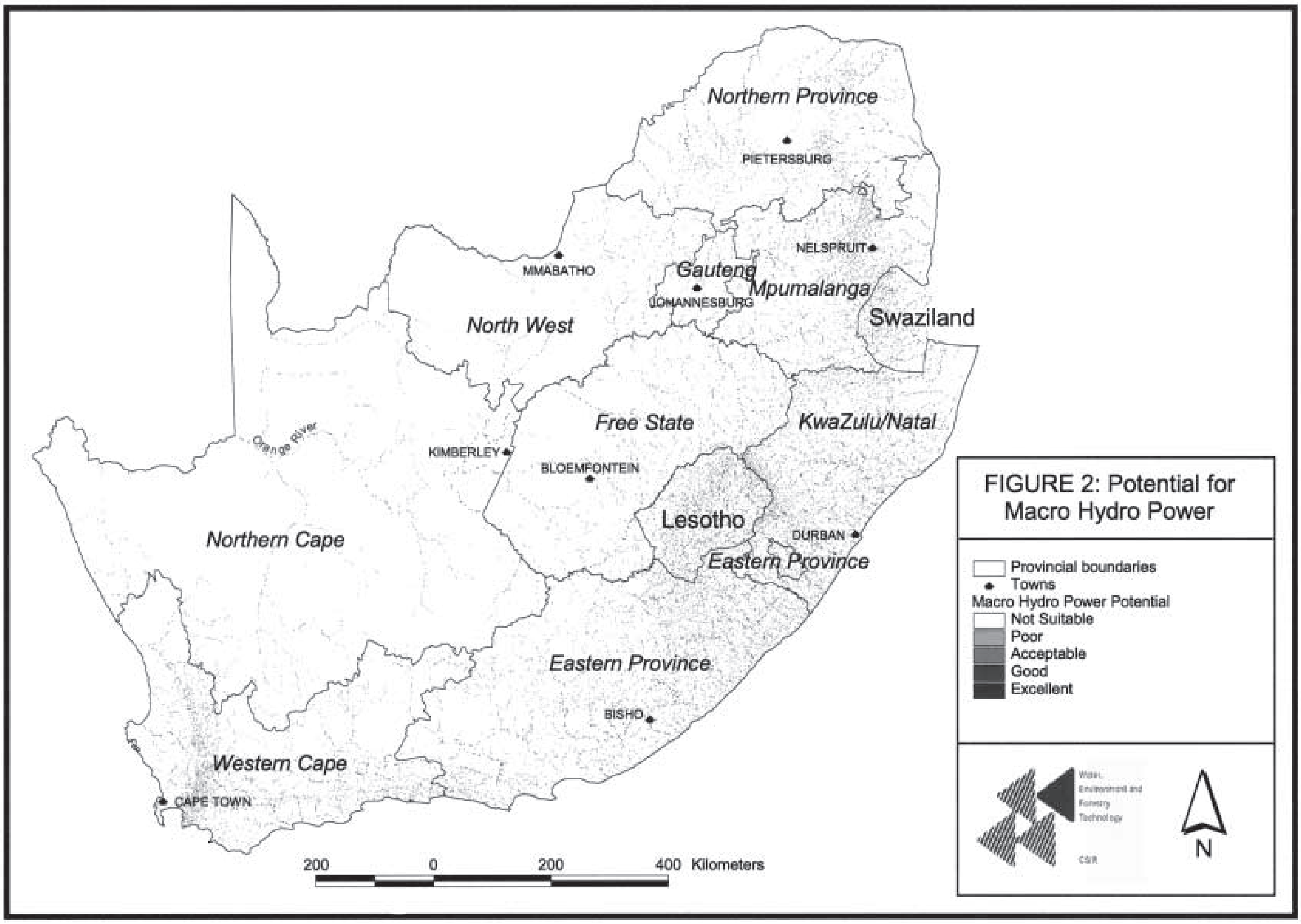


FIGURE 2: Potential for Macro Hydro Power

interruption of flow. These interruptions were due to errors in the altitude data, and the cumulative sequence continued when the altitude values were corrected. A good fit (small lateral divergence) was finally obtained between the two maps. The result was a synthetic river network of cells with attributes of cumulative flow volume for each cell.

The macro-hydro power potential was then estimated using Equation (2):

$$\text{AEP (kWh yr}^{-1}) = 9.8\ (\text{m s}^{-2}) \times \tan(\Theta) \times \text{Reach} \times \text{CMAFV}\ (\text{m}^3\ \text{yr}^{-1})/3{,}600\ (\text{s}) \quad (2)$$

where: AEP = Annual Energy Potential, in kilowatt hours per year

9.8 = acceleration due to gravity, in metres per second squared

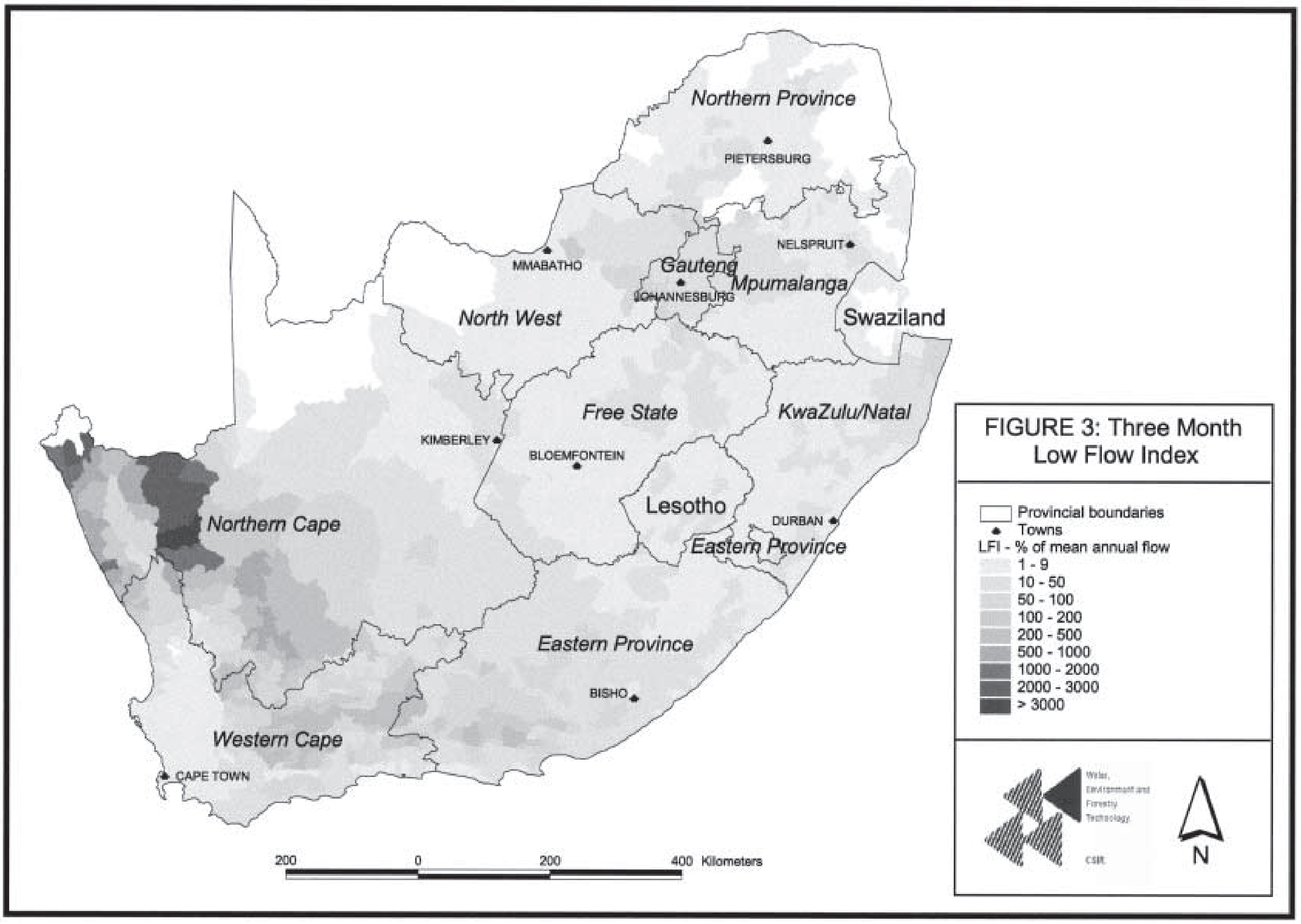
Θ = river gradient, in radians

Reach = river reach length (1,000 m)

CMAFV = cumulative mean annual flow volume, in metres cubed per year

3,600 = the number of seconds per hour.

This approach did not take into consideration the inefficiency of conversion to power. COV and LFI values were not included, as macro-hydro power requires the construction of large dams for water storage to supplement power generation during times of low flow. Reservoir capacity could be estimated using COV and LFI indices derived above, however.



RESULTS

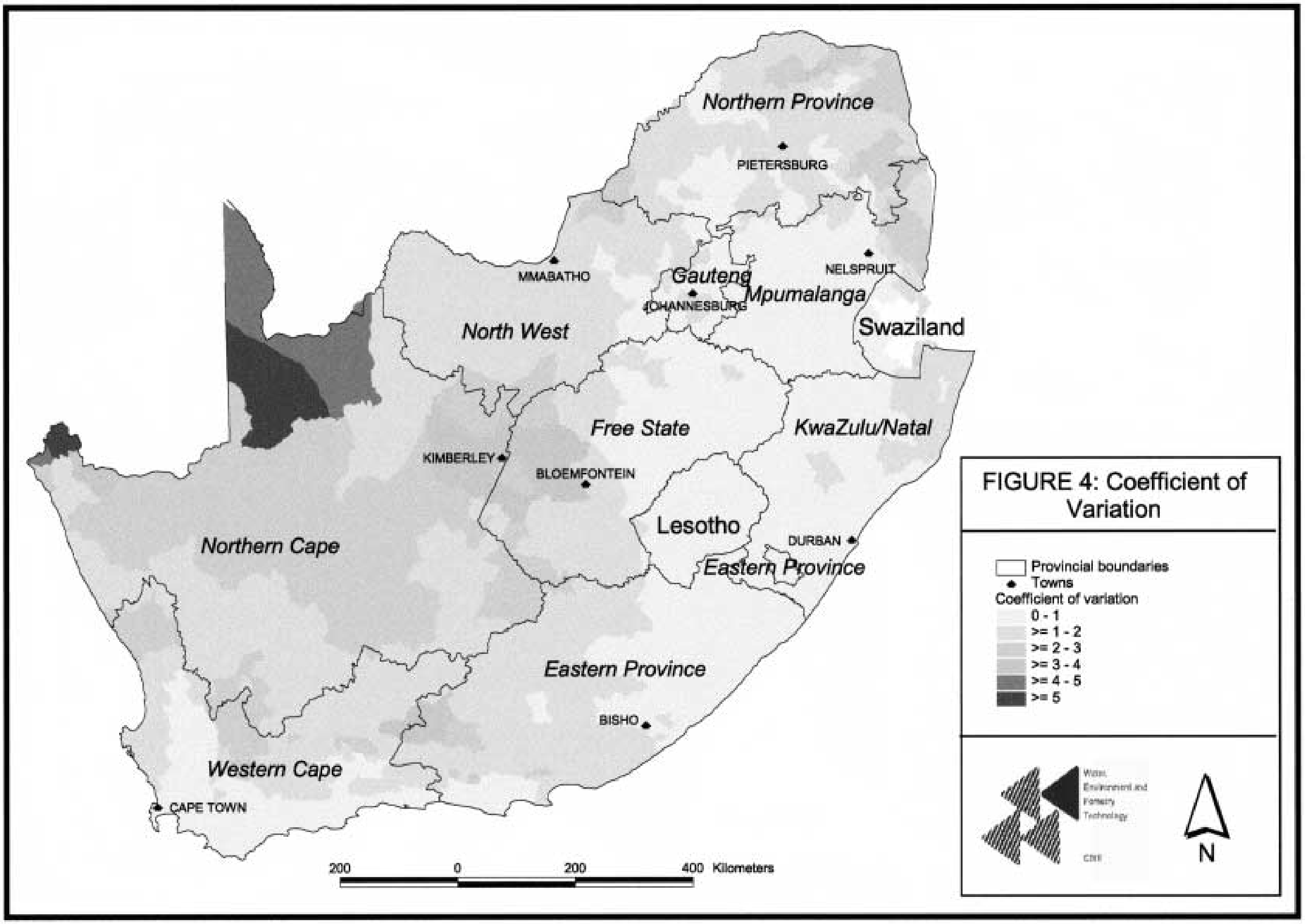
The estimates of AEP were grouped into several classes of suitability for hydro power generation. For micro-hydro these are:

Not suitable: <1,000 kWh yr^{-1} per km^2
Poor: 1,000–10,000 kWh yr^{-1} per km^2
Acceptable: 10,000–30,000 kWh yr^{-1} per km^2
Good: 30,000–100,000 kWh yr^{-1} per km^2
Excellent: ≥100,000 kWh yr^{-1} per km^2.

For macro-hydro the resulting classes are:

Not suitable: <10^5 kWh yr^{-1}
Poor: 10^5–10^6 kWh yr^{-1}
Acceptable: 10^6–10^7 kWh yr^{-1}
Good: 10^7–10^8 kWh yr^{-1}
Excellent: >10^8 kWh yr^{-1}.

The areas most suitable for micro-hydro power generation were found to be in the foothills of mountains, and in source areas of the catchments (Figure 1). In particular, the Lesotho Highlands and the mountains on the eastern border of Lesotho, the north eastern escarpment (between Pietersberg and Nelspruit), the mountainous areas of the western Cape, and many of the eastern Cape rivers showed excellent potential for micro-hydro power generation, with annual energy potential values exceeding 100,000 kWh yr^{-1}. However, site-specific studies are required for final selection, as proximity to settlements



requiring power supply and construction possibilities are important influential factors.

The areas with greatest potential for macro-hydro power were shown to be along the major rivers, especially near the mouths of rivers, where the volume of water is greatest, and in places along the Orange River (Figure 2).

Figure 3 illustrates the three month LFI, and Figure 4 illustrates the COV on a national scale. The highest variation in river flow was found to be in areas of the northern Cape, which corresponded to low potential for micro-hydro power. Cessation of flow is common in the western part of this province; thus micro-hydro power is not recommended in this area. A similar pattern is observed in the three month Low Flow Index.

DISCUSSION

The potential for micro-hydro power was found to be best where the variation in MAR is lowest. COV represents a range of variation over years, thus providing an indication of the frequency of low flow, and LFI represents the severity of flow reduction. Together, these can be used to rule out areas not suitable for micro-hydro power due to unreliable flow regimes. For example, in arid areas of the country, micro-hydro power can be considered a non-starter because of the enormous variation in flow rate and the very high probability of no flow at all.

There are several other factors which need to be considered when assessing the potential for micro-hydro power, such as cost-effectiveness, proximity to settlements requiring the power, risk of damage to equipment and environmental impacts. These factors need to be quantified and weighed up against the cost-effectiveness and logistical possibilities of providing power through connections to the national grid or other means, before proceeding with micro-hydro power development.

Further work should therefore include detailed investigations of suitable sites (as determined by this preliminary assessment), and investigations of alternative power supply options. Field assessments of suitable sites will include geological and topographical studies, flow potential and access studies, and assessment of flow diversion possibilities. Preliminary investigations of opportunities to exploit wind power, solar power and biomass power have been undertaken by Muller (1999).

CONCLUSION

This paper has shown how a combination of data sets and the analytical procedures within GIS can be employed to provide rapid and cost-effective investigations, in this case of macro- and micro-hydro power potential in South Africa. These results are preliminary however, and require further investigation. The technique employed enables researchers to focus quickly on areas showing the greatest potential for further investigation. It appears that South Africa does have potential for further expansion of macro-hydro power. The possibilities for micro-hydro power look promising, and further investigation is required. This would include a look at site-specific needs, and an independent economic assessment is required to prove the economic viability of possible power projects.

ACKNOWLEDGEMENTS

We would like to thank Dineke Vink for assistance with map production, and CSIR, Eskom Corporate Technology and the Department of Minerals & Energy Affairs, who provided equal financial assistance.

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