An assessment of invertebrate-based target flows for the River Itchen, Hampshire

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Non-technical summary

How much river flow is needed to ensure healthy freshwater ecosystems? This is a question that has exercised environmental managers for decades and one that is being made even harder by the prospect of climate change. Nonetheless, it is critical to balancing the water demands of society with the needs of the environment.

In the case of the River Itchen, the Environment Agency approached the task using long records of gauged river flows and in-stream macroinvertebrate abundance. These aquatic insects, worms, snails, and other creatures live on or amongst channel sediments and are very sensitive to changing river volumes and water quality.

By analysing data collected since the late 1980s, the Agency observe that marked changes in the spring invertebrate community appear when the preceding summer low flows in the lower Itchen (MU5) fall below 237 Ml/d. Below this threshold there are much fewer olive mayfly, anglers curse mayfly, blue winged olive mayfly, and freshwater shrimp.

The Agency also predicts the abundance and types of macroinvertebrates using a statistical model that combines data from several sites. This enables the setting of flow targets that are consistent with those in other rivers, whilst taking into account some of the sampling uncertainties. The statistical model predicts that a "hands off" flow of 198 Ml/d is needed to avoid long-term harm to the river's ecosystem.

However, independent assessment of the same data suggests that a target flow of 198 Ml/d is not sufficiently precautionary. This is because the target was extrapolated beyond the range of any data for the lower Itchen. In fact, river flows this low have only been recorded during the severe drought of 1976, for which there are no macroinvertebrate data. The closest analogue with data was the summer of 1990. During this drought minimum flows fell to 223 Ml/d and intended environmental objectives were not met at several sites.

There are other limitations in the Agency's approach. Some river flow targets are based on average summer conditions which mean that compliance can only be assessed retrospectively. Intervening winter spates are also ignored so the targets may not be sufficient in the event of a dry winter following a dry summer. Other factors such as changing river water temperature, or sediment loads are also disregarded.

Using a statistical model that includes winter flows it was found that an average summer target flow of 237 Ml/d would realise environmental objectives at MU5 in 10 out of 11 years. Clearly, flow targets set for the lower river will not affect the achievement of flow targets in the upper river (where there is little or no abstraction). However, when there has historically been good invertebrate status in the upper and middle Itchen, minimum summer flows of at least 289 Ml/d would be expected in the lower river.

Over coming decades it is anticipated that climate change will modify river flows by shifting towards hotter, drier summers and milder, wetter winters. These changes could reshape the annual regime of chalk aquifer recharge and hence flows in the River Itchen. Climate modelling shows that beyond the 2040s there is a growing chance that the Agency's target flows would not protect the wider ecosystem in a significant fraction of years.

It is concluded that a long-term view should be taken with regard to monitoring the changing ecological status of the river, and to reviewing the allocation of water amongst different uses. In the meantime, there is evidence that the Agency's target flows could fail to deliver intended benefits, particularly in the wake of dry winter conditions.

Technical summary

With growing concerns about water security and allocation under climate change, there are calls for greater certainty in the provisioning of water for fluvial ecosystems.

This Technical Note offers an independent assessment of the methodologies, key scientific findings, and processes of the Environment Agency's Review of Consents for the River Itchen, Hampshire. Attention is focused on targets emerging from an assessment of low flow requirements of the in-stream macroinvertebrate community.

Two methods were applied by the Agency. The first was based on a linear regression equation relating LIFE (Lotic Invertebrate Flow Evaluation) scores in spring, to low flow statistics in the preceding summer (Q95). The model estimates the summer flow requirement (with confidence intervals) to achieve a LIFE score indicative of a healthy macroinvertebrate community. The second method statistically clusters macroinvertebrate data to identify low flow thresholds beyond which the community abundance and structure are markedly different. The Agency's analysis identified three target flows:

- Target 1: The long-term average summer Q95 flow in each Management Unit (MU) should be greater than 0.951 of the 1987-2001 mean (that is 262 Ml/d at Allbrook and Highbridge, MU5);
- Target 2: The minimum river flow should not fall below 0.719 of the 1987-2001 mean (that is a "hands off flow" of 198 Ml/d in MU5);
- Target 3: The annual summer Q95 should not fall below 0.861 of the 1987-2001 mean more often than recorded in the gauged flow record of each MU (that is 237 Ml/d at MU5 once every 5 to 6 years).

The Agency made several assumptions to arrive at the target flows, including:

- Summer low flows are the most important determinant of macroinvertebrate status in the following spring;
- Factors such as water quality and habitat availability do not generally limit the status of the macroinvertebrate community within the River Itchen main channel;
- The 1987-2001 baseline period is representative of longer-term river flow conditions;
- Winter spates and multi-year 'drought history' do not affect sampled macro-invertebrate assemblages in spring.

Some of the most important assumptions were tested via further modelling and analysis of the macroinvertebrate and river flow data used by the Agency. A multiple regression model was constructed in order to test the sensitivity of the targets to the assumed summer and winter flow regime. Reference was also made to recent experiments which show the failure rate of the "hands off" flow target under climate change. These investigations suggest that:

- Compliance with a long-term average summer Q95 (Target 1) flow of 262 Ml/d at MU5 will be impossible to assess in real-time. This is because the flow statistic has to be calculated from a moving window of several years' gauged flows.
- A summer Q95 "hands off" (Target 2) flow of 198 Ml/d fails to deliver the annual summer Q95 (Target 3) flow of 237 Ml/d. In other words, there is dependency between the flow targets at a given site.
- A Target 2 flow of 224 Ml/d is on average needed to achieve the annual summer Q95 (Target 3) flow of 237 Ml/d in MU5. This estimate assumes that the long-term ratio between the minimum flow and summer Q95 has not been changed by abstractions.

- A Target 3 flow of 237 Ml/d might not achieve environmental objectives on average one year in 11 depending on the magnitude of winter Q5 flows. In other words, there is a dependency between the flows of successive seasons and ecological outcomes.
- Historically when there has been good invertebrate status in the upper and middle Itchen, a minimum summer flow of at least 289 Ml/d is expected in the lower river.
- The empirical relationship between invertebrate status and antecedent flows may not necessarily hold for the future if other conditions in the river change such as water temperature or sediment load.

Climate change projections for the 2020s and beyond signal rising air and water temperatures, drier summers, and wetter winters in southern England. This outlook would reshape the intra-annual flow regime and hence the potential for aquifer recharge and recovery of drought-stressed macroinvertebrate communities. Therefore, it is recommended that any revision to existing targets and/or extension of macroinvertebrate assessment to other catchments should pay due attention to both winter and summer flows.

It is concluded that the proposed Stage 4 Target flow regime based on summer Q95 flows is sufficiently precautionary provided that failure to achieve environmental objectives one year in 11 is an acceptable level of risk. However, this conclusion is tempered by two caveats:

- First, the Target 2 flow should be revised upwards to ensure that the existing Target 3 flow can be achieved;
- Second, there should be sufficient flexibility in water governance structures and across the abstraction licensing regime to adaptively manage targets should seasonal flows begin to shift in response to climate and/or land use change.

Beyond the 2040s, there is increasing likelihood that the current set of target flows will not protect invertebrate communities (and hence the wider ecosystem) in a significant proportion of years. In the interim, changes to thermal and water quality regimes are expected to add to existing pressures on the river's ecosystem.

Finally, having reviewed the Agency's approach to defining target flow thresholds in the Itchen it is acknowledged that the abundance of ecological and (long-term) hydrological data provides a strong starting point. However, there remain wider questions about the transferability of the methodologies to more data-sparse rivers.

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1. Introduction

The Environment Agency has recently completed a Review of Consents (ROC) for the River Itchen Special Area of Conservation (SAC) in line with the requirements of the European Union Habitats Directive. As a consequence, the Agency has proposed amendments to nine abstraction licenses, including public water supply[1]. This is to ensure that there is sufficient water in the river to protect populations of designated species, and to safeguard salmon migration, even in very dry summers. However, it is recognised that these measures alone will not restore the SAC to favourable conditions because of unregulated impacts (arising from, for example, sediment carried in runoff from neighbouring agricultural land).

The purpose of this Technical Note is to provide an independent assessment of the methodologies, key scientific findings and processes involved in the Agency's River Itchen ROC. Particular attention is focused on the target river flows defined by the assessed requirements of the in-stream invertebrate community.

2. Defining environmental flows

Environmental flow methodologies seek to determine the quantity and quality of water required to achieve specific predefined ecological, social or economic objectives (see Petts, 2009). In some regions objectives may be specified by international law. This is the case for Good Ecological Status – defined with respect to the fauna and flora communities at reference sites – under the EU Water Framework Directive (WFD). There are hundreds of approaches for calculating the environmental flow requirement, but most can be grouped into one of four main categories (Acreman and Dunbar, 2004; Tharme, 2003):

1. Look-up tables that are based on simple rules-of-thumb such as percentages of the mean flow or an exceedance percentile (such as the 95th percentile of the daily mean flow, Q95) taken from the flow duration curve (FDC).
2. Desk top analyses such as the Range of Variability Approach (RVA) set hydrological targets for the whole river flow regime, including peak, average and low flows, in order to safeguard ecosystem integrity.
3. Functional analyses such as the Building Block Methodology (BBM) are based on the premise that the flow regime can be disaggregated into units with specific functions such as habitat maintenance, channel flushing, minimum flows for migration, and so forth (e.g., Acreman et al., 2009).
4. Habitat analysis and modelling tools such as PHABSIM that establish functional relationships between simple indices of available habitat and the physical properties of flow volume, depth and velocity via rating curves (Maddock, 1999).

The Agency's approach is based on the concept of invertebrate flow requirements developed by Extence et al. (1999). The underlying premise is that the river velocity and flow regime directly affect invertebrate respiration and feeding, or indirectly through habitat availability. ***The Agency assumes that other factors such as water quality and habitat availability do not generally limit the status of the macroinvertebrate community within the River Itchen main channel*** (Exley, 2003; 2006).

The following sections assess the evidence compiled by Exley (2006) and Atkins (2007) to develop a Stage 4 Target Flow Regime for the River Itchen. Where feasible this review used the same river flow (Annex 1 and 2) and macroinvertebrate data as earlier studies.

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[1] http://www.environment-agency.gov.uk/static/documents/Business/river_itchen_sac_1888068.pdf

3. The Agency's approach to defining low flow thresholds

Significant changes in the composition and abundance of chalk stream taxa are known to arise from natural variations in the flow regime (MacNeil et al., 2000; Wood and Armitage, 2004). Therefore, it follows that provided certain flow criteria are met, the invertebrate community will in the long-term be in favourable status. Exley (2006) describes two methods of defining baseline flow targets to achieve desirable environmental outcomes – expressed in terms of LIFE (Lotic Invertebrate Flow Evaluation) scores recorded at the Agency's routine sampling sites in the River Itchen.

Macroinvertebrate and discharge statistics collected for six management units (MUs) since the mid 1980s reveal that spring LIFE scores were strongly correlated with the standardized summer (April to September) Q95 flow in the previous year (Figure 1). The resulting linear regression model can estimate the summer flow required for a given spring LIFE score. This model suggests that 0.805 standardized flow units are needed to achieve a target LIFE score of 0.974 relative to the value predicted by RIVPACS (Clarke et al., 2003). The actual flows and associated confidence limits are given for each MU in Table 1.

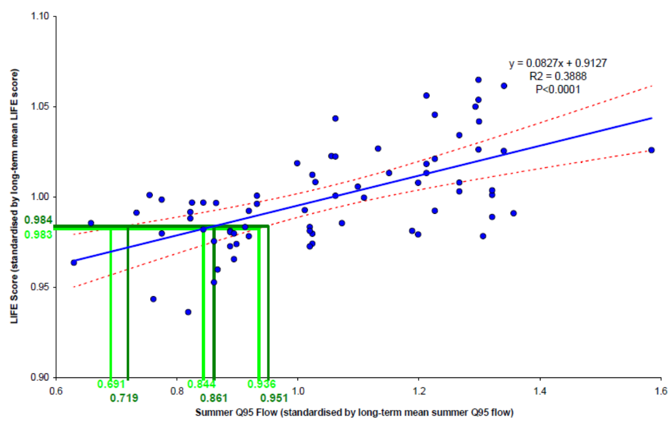


Figure 1 The generalised relationship (and 95% confidence intervals) between LIFE score (standardised by long-term mean LIFE score) and summer Q95 flow (standardised by long-term mean summer Q95 flow). Flow thresholds between 0.861 and 0.844 standardised flow units are indicated by the green lines.

Source: Exley (2006)

Method two used multivariate ordination (i.e., clustering) of the invertebrate data to reveal that significant changes in the community begin to be observed between 0.861 and 0.844 standardised flow units (Figure 2). Samples taken at times with flows below the latter threshold had much lower counts of olive mayfly, anglers curse mayfly, blue winged olive mayfly, and fresh water shrimp. Given that no significant community changes were detected above 0.861 standardised flow units, this threshold was considered to be more precautionary and was established as the target summer Q95 flow. The predicted spring LIFE score for this flow is 0.984 (Figure 1). Upper and lower 95% confidence limits for flows that could yield the same LIFE score lie in the range 198 to 262 Ml/d (Figure 1 and Table 1).

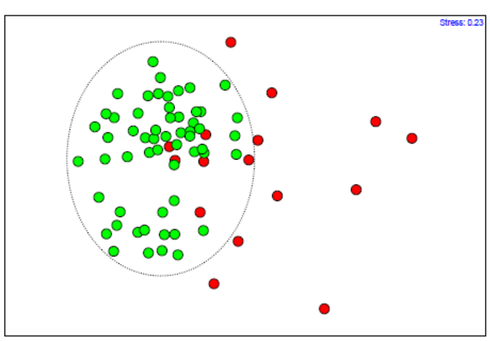


Figure 2 Ordination of River Itchen samples showing samples collected when summer Q95 flow was greater than or equal to 0.861 standardised flow units (green), and samples collected when summer Q95 flow was less than or equal to 0.844 units (red). These sample groups were shown to be significantly different (p=0.001) and are respectively equivalent to 237 and 232 Ml/d in the lower Itchen. Source: Exley (2006)

Table 1 Management Unit (MU) specific summer Q95 flow thresholds (Ml/d). Source: Atkins (2007).

MU	1987-2001 summer Q95	Regression model (0.805) [standardised by RIVPACS]			Multivariate ordination (0.861) [standardised by site means]		
		Lower 0.580	Mean 0.805	Upper 0.909	Lower 0.719	Mean 0.861	Upper 0.951
1	27.6	16.0	22.2	25.1	19.8	23.8	26.2
2	96.6	56.0	77.8	87.8	69.4	83.2	91.9
3	26.7	15.5	21.5	24.2	19.2	23.0	25.4
4	256.2	146.7	203.7	229.9	181.8	217.9	240.7
5	275.4	159.7	221.8	250.3	***197.9***	***237.3***	***262.0***
6	270.2	156.6	217.6	245.6	194.2	232.8	257.1

The flow thresholds derived from macroinvertebrate community data were used by Atkins (2007) to construct risk profiles associated with each flow. The overlapping confidence limits and targets in Table 1 provide a "warning band" above which the invertebrate community remains in healthy condition; within the band there is heightened risk of flow induced impacts on the abundance of certain groups; below the band there is a high risk that the macroinvertebrate communities will suffer long-term loss of abundance and some family groups. Three flow Targets were established with these risks in mind:

1. Long-term average summer Q95 flow in each MU should be above the upper 95% confidence level for the 0.861 target (that is 262 Ml/d in MU5);
2. River flow should not fall below the lower 95% confidence level for the 0.861 target (that is a "hands off flow" of 198 Ml/d which is equivalent to the minimum flow);
3. Annual summer Q95 should not fall below the mean 0.861 target more often than recorded in the gauged flow record of each MU (that is 237 Ml/d at MU5 once every 5 to 6 years).

The above flow criteria were benchmarked to river flow records at Allbrook and Highbridge (MU5 and MU6) on the premise that 83% of the total public water supply annual licensed abstraction in the catchment is from sources located in the Lower Itchen. It was assumed that if the target flows are achieved at downstream MUs, then all upstream MUs will comply.

Note that the Target 1 and 2 flows are products of statistical modelling and do not refer to observed thresholds in invertebrate data. However, the Target 1 flow is comparable to the average flow in September at MU5 and MU6 (270 Ml/d) predicted by models as necessary for upstream migration of salmon beyond Woodmill Pool (Atkins, 2006). Although the Agency is no longer confident in the 270 M//d target to protect salmon migration, the following analysis presents evidence from a very different method that flows of this order have been associated with good ecological status throughout the river, not just at MU5.

The next section assesses the extent to which the underlying assumptions of the statistical modelling are justifiable, and hence whether the recommended summer flow targets based on macroinvertebrates are sufficiently precautionary.

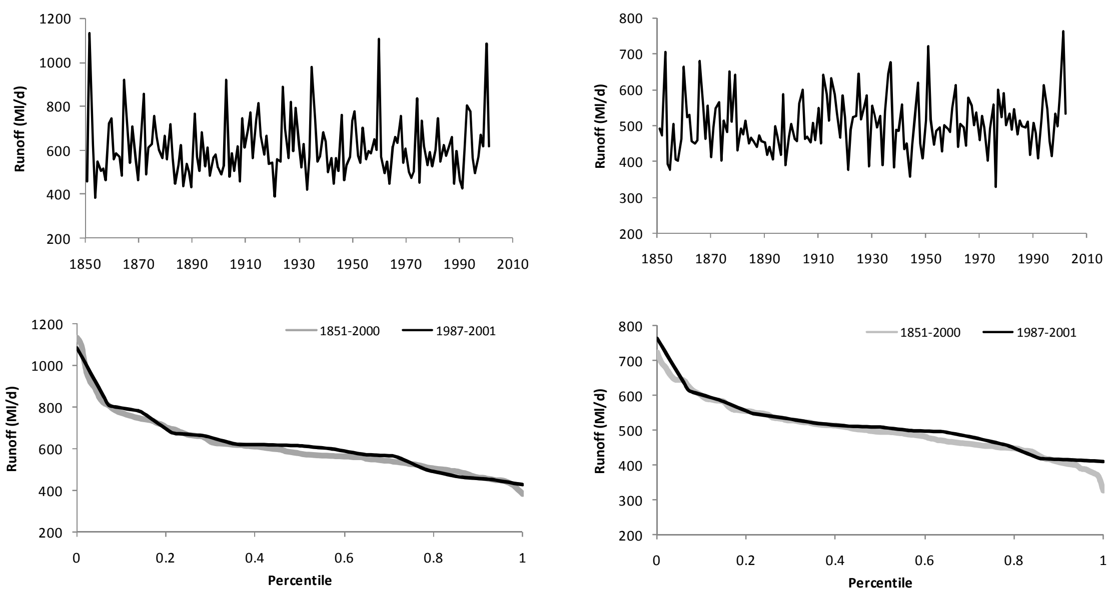
4. Evaluation of invertebrate flow targets

Setting aside the issue of whether the recommended invertebrate flow targets take account of the wider flow requirements of the chalk stream habitat (Atkins, 2007), several legitimate questions remain about the River Itchen ROC methodology.

4.1 How representative is the baseline period of long-term flows?

The period chosen to benchmark the hydrological data and sample macroinvertebrate communities is noteworthy because of the persistent drought of 1988-1992, summer 1995 heatwave and drought, followed by the widespread autumn and winter flooding of 2000/1 (Marsh, 2001). There has since been the record-breaking heatwave in summer 2003, and localised flash flooding in the summers of 2004 and 2007. However, when reconstructed flow duration curves for 1987-2001 are compared with those for 1851-2000 the correspondence is remarkable (Figure 3). In fact, these flow duration curves are statistically indistinguishable (despite the presence of the 1976 drought). Therefore, ***it is concluded that for <u>naturalised</u> seasonal mean flows at least, the baseline period is representative of longer-term river flow conditions***.

Figure 3 Reconstructed winter (left column) and summer (right column) monthly mean runoff series (top row) and flow duration curves (bottom row) for the River Itchen. Data show naturalised runoff and are, therefore, indicative of seasonal flows that would have existed in the absence of artificial influences. Data source: Jones et al. (2006).

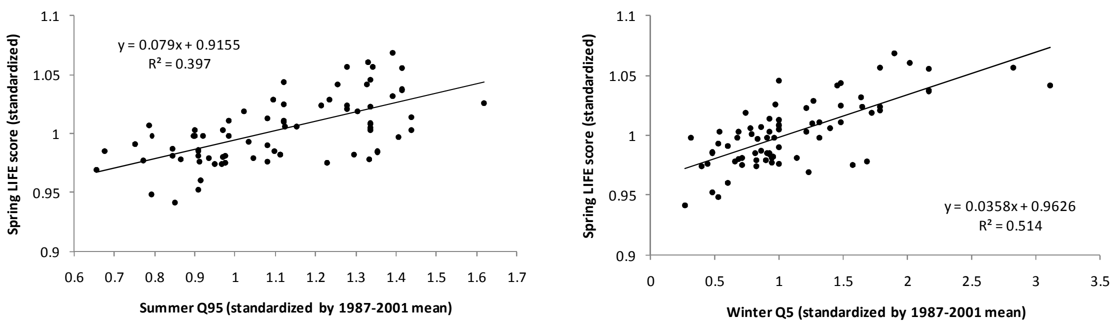


However, increasing surface and groundwater abstractions up to the late 1980s have exacerbated conditions during drought years by reducing water volumes, depths and velocities. For example, by the end of the 1992 drought, observed residual flows were depressed by ~37% compared with estimated natural flows (Wilby, 2008). This complicates the task of estimating return periods for low flows associated with particular LIFE scores.

4.2 How important are winter flows to macroinvertebrate status?

The flow targets presented in Table 1 were based on the generalised relationship between standardised spring LIFE scores and standardised summer Q95 flows at eight sites in the River Itchen. However, the underlying linear regression model explains less than 40% of the observed variation in LIFE scores, meaning that over 60% of the variability in the macroinvertebrate data is explained by factors other than summer Q95 (see Figure 4, left panel). Exley (2006) suggests that modest levels of predictability are to be expected given the wide range of environmental (i.e., non-flow) and biotic factors influencing invertebrate communities. There are also acknowledged uncertainties inherent to the sampling of macroinvertebrate variability in space and time (Clarke, 2009).

Figure 4 Relationships between spring LIFE score and preceding summer Q95 (left plot) or winter Q5 (right plot) based on data combined from eight sites in the River Itchen. All data were standardized by their respective seasonal means derived from available information during the period 1987-2001.



Depending on the life histories of individual taxa and their lagged responses to flow variations, temporal autocorrelation could be occurring between successive macroinvertebrate samples collected at each site (Dunbar and Clarke, 2005). For example, a low LIFE score in autumn could lead to a low LIFE score in the following spring, and *vice versa*. However, this does not appear to be the case for macroinvertebrate samples collected in the Itchen. Here the autocorrelation ($r<0.20$) between successive autumn and spring LIFE scores is statistically insignificant when all sites are combined.

The absence of autocorrelation in LIFE scores leaves antecedent flow as a plausible explanatory variable. High flow episodes are known to scour sediment from gravel habitats, provide refuge for invertebrates that prefer fast flowing water, and affect macrophyte status in the Rivers Test and Itchen (Wilby et al., 1999). Both Exley (2006) and Atkins (2007) note that “spate” flows are important to the health of macroinvertebrate populations in the Itchen but do not pursue the point any further given that these high flows are not adversely affected by abstractions. However, preliminary results presented by Exley (2006) show that preceding winter Q5 (and to a lesser extent Q50) flows are significantly related to spring LIFE scores. The former relationship is clearly evident in Figure 4 (right panel). Indeed, the winter Q5 flow explains more than 50% of the variability in spring LIFE scores.

When antecedent summer Q95 and winter Q5 are combined in the same multiple linear regression the amount of explained variance in spring LIFE scores is 58% even after adjusting for sample size (see Annex 3 and Figure 5). When tested against macroinvertebrate data for 2004 (which was not used for calibration), the model predicts the standardised LIFE scores observed in MU1a, MU3, and MU4c to within ±0.02 units. This is considered a promising outcome given that the prediction is based on data collected during and after the extraordinary heatwave of summer 2003.

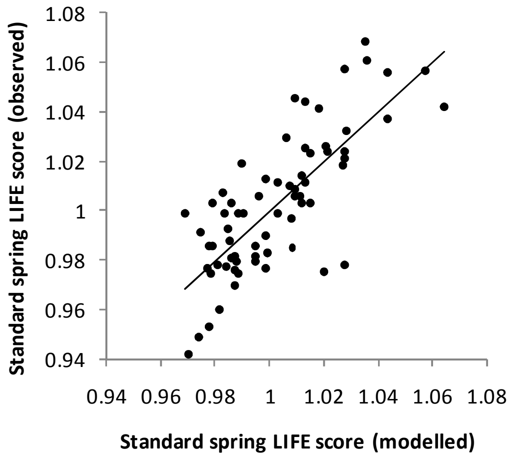


Figure 5 Observed and modelled spring LIFE scores for eight sites in the River Itchen. Modelled data were derived from a multiple regression model fit to preceding summer Q95 and winter Q5 flows up to the year 2003. All data were standardized by their respective 1987-2001 means.

Note that even the multiple-regression model is also based on individual points taken from the flow duration curve (i.e., seasonal Q95 and Q5). However, the importance of restoring and/or maintaining hydrologic *variability* is also recognised as central to sustaining ecological integrity (Petts et al., 1995; Poff et al., 1997; Richter et al., 1997). Likewise, the potential influence of long-term trends in water temperature on macroinvertebrate assemblages should not be overlooked. These factors are clearly much more problematic to manage than fixed target flows, but do merit further consideration.

The two season regression model provides a basis for evaluating the potential efficacy of summer flow targets given hydrological conditions in the following winter. For example, consistently depressed winter Q5 flows could strengthen the case for more stringent flow targets in the preceding summer if spring LIFE scores are to be maintained. Under median winter Q5 flow conditions, ***the multiple regression model suggests that a summer Q95 flow of 220 Ml/d is needed to secure a healthy macroinvertebrate community on average one in two years*** (i.e., a spring LIFE score of 0.984).

The same model can be used to estimate the winter Q5 flow of specified return period that would counteract the average summer Q95 flows listed in Table 1. For example, target summer flows of 237 and 262 Ml/d would not realise the intended spring LIFE score, if followed by depressed winter Q5 flows with return periods greater than 1 in 11, and 1 in 23 years respectively (Figure 6). In other words, ***the Target 3 flow of 237 Ml/d might not achieve environmental objectives on average one year in 11 due to a lack of winter spate flows***. This makes the case for establishing conjunctive seasonal flow targets that can be adjusted to reflect anticipated increases in the ratio of winter to summer precipitation (Murphy et al., 2009).

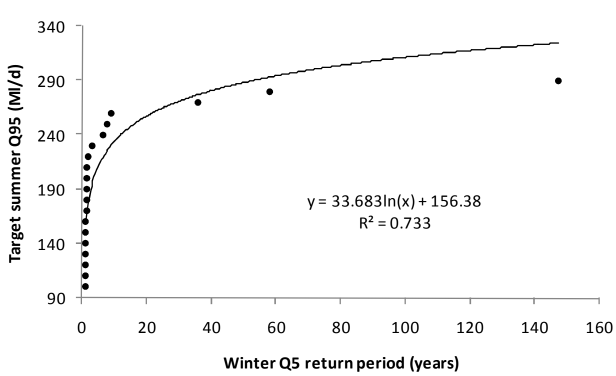


Figure 6 Modelled summer Q95 target flow in MU5 needed to achieve a standardised spring LIFE score of 0.984 in relation to the assumed winter Q5 flow regime. The given return periods (years) are for *depressed* winter spates.

In the River Itchen the summer Q95 flow has historically been weakly (but not significantly) positively correlated with the winter Q5 flow ($r \sim 0.2$). In other words, lower than average summer base flows are typically followed by lower than average winter spates. So once a low flow episode begins, ameliorating winter spates are less likely too. This is consistent with the reported clustering of drought episodes in England and Wales (Marsh et al., 2006), so ***the long-term health of the river will depend on the ability of the macroinvertebrate community to rapidly recover from protracted periods of low flow stress***.

4.3 How precautionary are the flow targets?

The Agency flow targets assume that a generalised LIFE response equation can be constructed by blending macroinvertebrate and river flow data from different sites (Figure 1). When subjected to careful scrutiny, it is evident that predicted LIFE scores depend on the method of flow standardisation, uncertainty from within-season sampling of taxa, as well as downstream variations in habitat type and channel geometry (Dunbar and Clarke, 2005).

As noted before, the flow targets in Table 1 were derived from a generalised relationship between standardised spring LIFE scores and standardised summer Q95 flows using sites throughout the Itchen. Both the LIFE scores and summer flows were standardised by their respective site means. This method neglects the considerable *in situ* variability in river flows which is greatest at MU1 and MU3, and least at MU4 and MU5. For example, during the period for which there are macroinvertebrate data, the standardised summer Q95 varies between 0.507 and 1.407 at MU1, compared with 0.841 to 1.352 at MU5. Consequently, ***the estimated LIFE score at MU5 associated with a summer Q95 of 0.719 can only be extrapolated from the generalised relationship since this value lies outside the range of the calibration data*** (Figure 7).

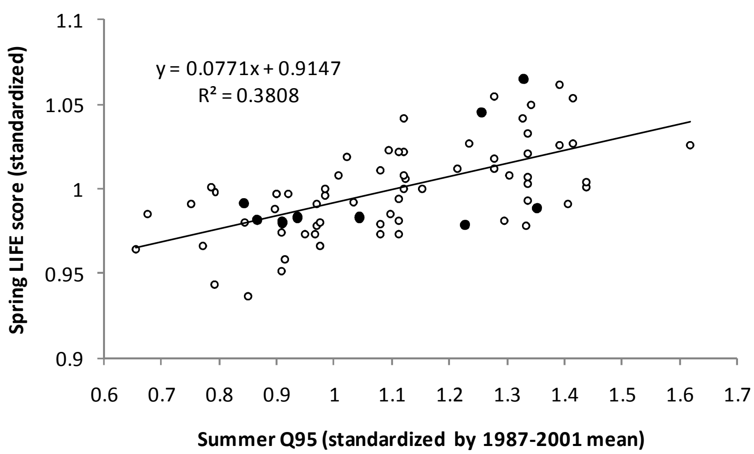


Figure 7 The generalised relationship between LIFE score (standardised by each site's long-term mean LIFE score) and summer Q95 flow (standardised by each site's long-term mean summer Q95 flow). [Note that this plot and regression equation differs slightly from those shown in Figure 1 because data have been included from spring 2004]. Black dots show observations for MU5.

The Target 2 flow estimated for MU5 using the Agency's generalised LIFE score model is 198 Ml/d. Flows this low have been recorded on only 15 days during the period 1976-2004, and all of these fell within a single year, 1976. This severe drought preceded macroinvertebrate sampling, so there are no data to assess whether the "hands off" flow would protect the macroinvertebrate community should a similar event recur. Indeed, for 1976 the standardised summer Q95 (0.722 at MU5) yields an estimated LIFE score of 0.972 for spring 1977, which represents below average macroinvertebrate status. Therefore, it is concluded that ***the Target 2 flow is unlikely to be sufficiently precautionary to achieve ecological objectives in the event of a drought as severe as 1976***.

The closest analogue to the Target 3 flow given in Table 1 (for which there are both gauged flows and macroinvertebrate data) is summer 1990. During this drought the summer Q95 flow at MU5 was 232 Ml/d, and the minimum flow was 223 Ml/d. According to the long-term relationship between the summer Q95 and minimum (Q100) (Table 2 and Figure 8), ***a Target 3 flow of 237 Ml/d in MU5 requires on average a "hands off" Target 2 flow of ~224 Ml/d***. Even then, macroinvertebrate samples collected in spring 1991 had standardised spring LIFE scores below the 0.984 target at three sites (MU1, MU4 and MU5). Individual data from Figure 7 suggest that when this LIFE score is observed at all upstream sites, a standardised flow of at least 1.1097 would be expected at MU5. Based on the historic ratio between the two metrics (Table 2), this equates to Target 2 and Target 3 flows of 289 Ml/d and 306 Ml/d respectively.

Table 2 Ratios between annual summer Q95 flow and annual minimum (Q100) flow in each MU using residual flows for the period 1976-2004.

Ratio	MU1	MU2	MU3	MU4	MU5	MU6
Q95:Q100	1.059	1.044	1.074	1.036	1.058	1.102

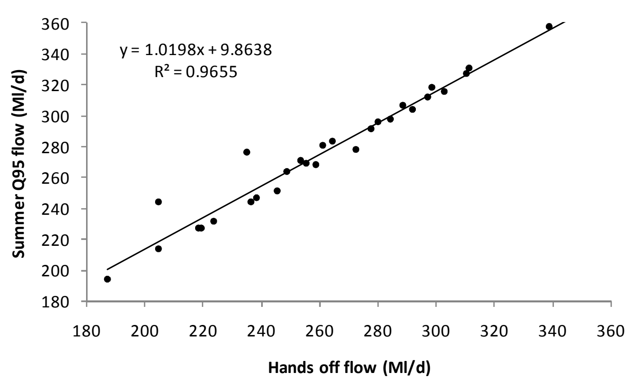


Figure 8 The historic relationship between the summer minimum (hands off) flow and associated summer Q95 flow in MU5. Note that relationship reflects artificial influences. For instance, the two main outliers (1978 and 1994) probably indicate lower than expected minimum flows due to abstraction.

4.4 How sustainable are the environmental objectives?

Atkins (2007) assert that the macroinvertebrate analysis currently *provides the most robust basis for setting target flows for the catchment as a whole*.

Previous thresholds based on a salmon entry model were dismissed on the grounds that extrapolated sections of the probability curve have a very high margin of error; the assumed causal relationship between residual flow and salmon entry could be a surrogate for other controls such as water temperature; non-flow factors such as structures at the tidal limit or fisheries removal are more important; salmon entry threshold flows for the Lower Itchen are not helpful in defining flow targets for upstream MUs 1 to 5; and there is no guarantee that improved salmon spawning would translate into a larger salmon population (Atkins, 2007).

Similarly, macrophytes were rejected as a basis for establishing target flow regimes because of lack of data, and strong influences by non-flow factors (including nutrient enrichment, shading, weed management, swan grazing, and substrate). Further research is already in hand to better quantify the flow requirements of in-stream flora, such as Ranunculus.

In short, aspects of both the salmon and macrophyte evidence raised concerns when the "fair and reasonable test" was applied to Stage 3 flow thresholds. However, it has been demonstrated that – through license changes proposed by the invertebrate assessment (plus further reductions in licensed abstractions in June and July) – targets for spawning escapement may still be realised (Atkins, 2007). Furthermore, “hands-off” Target 2 flows are practicable for compliance testing because it will become immediately apparent from routine monitoring if residual flows drop below the target. Conversely, Target 1 and 3 flows require long-term monitoring before their respective percentiles can be computed, and hence compliance cannot be readily assessed.

For Target 1, “long-term” has not been defined, but is presumed to be of the order 20 years in order to detect potentially harmful shifts in average flows. ***Long-term changes in climate, groundwater recharge, and catchment land use (such as a switch to more bio-energy cropping) all have the potential to modify flow regimes and hence the sustainability of environmental benefits achieved through reductions in licensed abstractions***. For example, under the UKCIP02 Medium-High emissions scenario for the 2020s annual average recharge in the Test and Itchen is projected to decrease by 6% and annual Q95 flows by 8% (Entec, 2008).

Sensitivity analyses show that naturalised flows combined with high rates of climate change result in a low flow regime that is not dissimilar to the current situation (i.e., gauged flows) (Wilby, 2008). However, scenarios that combine historic abstractions with climate change result in lower flows than present (Figure 9). Under low, median and high climate change by the 2020s, a mean flow of 270 Ml/d for September would not be achieved in respectively 7, 9 and 25 years out of 30 years. Alternatively, historic abstractions would have to be reduced by ~60 Ml/d to achieve the same target flow under a median climate change scenario.

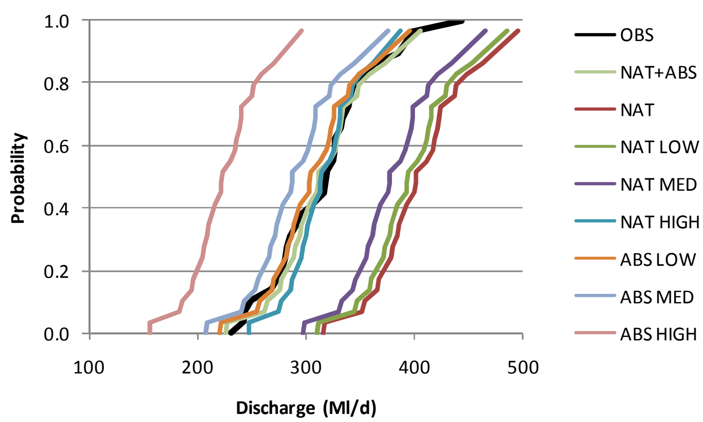
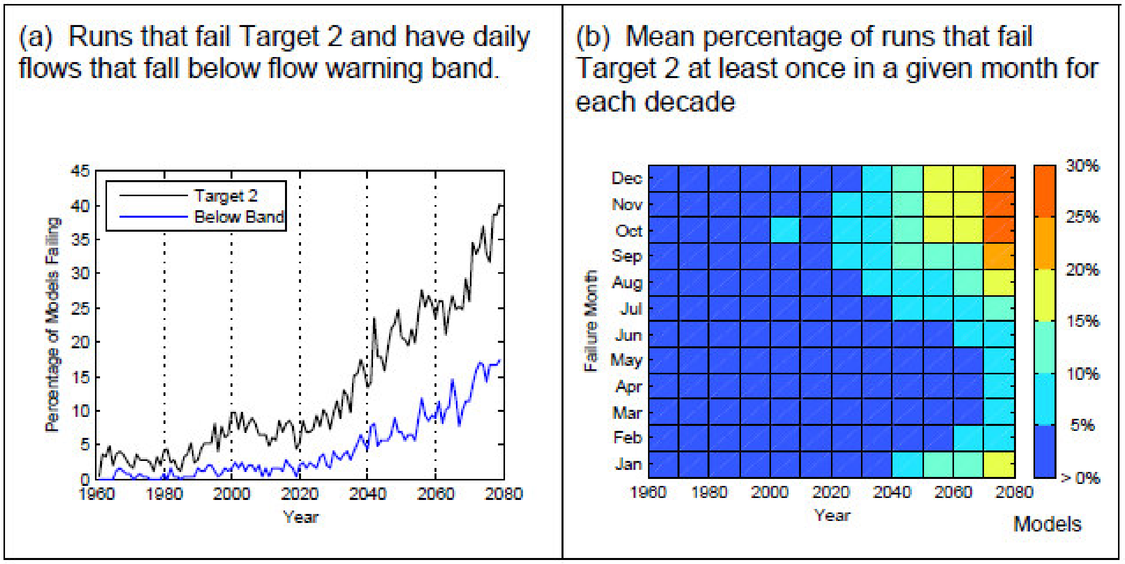


Figure 9 Sensitivity of naturalised (NAT) September mean flows in the River Itchen to historic abstraction (ABS) combined with LOW, MEDIAN and HIGH climate change factors for the 2020s. All flow duration curves are compared with respect to observed (OBS) 1961-1990 flows. Values for the climate change factors are respectively the 5th, 50th and 95th percentiles of the climate model ensemble. Source: Wilby (2008)

Climate change impacts inferred from a small number of scenarios may not fully reflect the extent of climate modelling uncertainty. The above results are, therefore, best regarded as sensitivity tests across a plausible set of climate changes. A more comprehensive assessment of risks requires downscaling from a much larger ensemble of climate models such as the *ClimatePrediction*.net (CPDN) experiment. Fortuitously, CPDN has already been used to evaluate changing flows in the River Itchen in relation to the three Target flows outlined above (Fung et al., 2009). During the period representing present-day (1961-1990) conditions fewer than 5% of the model runs generate daily flows below the Target 2 threshold (198 Ml/d), implying less than 1 in 20 year chance of failure. [However, this is an optimistic outcome because abstractions were not included in the catchment modelling]. By the 2040s the failure rate is ~20%, and by the late 2070s reaches ~40% of model runs (Figure 10a). These failures tend to be concentrated in the autumn months as decreased summer-autumn precipitation and increased evaporation cause a lengthening of the summer dry period (Figure 10b).

Figure 10 Failure rates for the Target 2 flow threshold projected by the 246-member ensemble of the *ClimatePrediction*.net experiment. Source: Fung et al. (2009).



The changes in autumn flows suggested by the CPDN scenarios point to increasing risks of failure of macroinvertebrate recruitment linked to loss of abundance and depleted over-wintering populations. Given that other properties of the fluvial environment (e.g., habitat availability, water temperature, and dissolved oxygen concentrations) are also expected to change and that new species could become established, there could be marked transformations of the ecosystem structure and function. The CPDN study further reinforces the case for paying more attention to potential changes in the winter (not just summer) flow regime, and associated ecological impacts.

5. Conclusions

Macroinvertebrate communities in chalk streams are known to be resilient to short-lived, historic droughts (Woods and Petts, 1994); it is less clear how the same assemblages might respond to episodes of reduced flows spanning multiple seasons, even years. Recent research into low flow controls on benthic and hyporheic macroinvertebrate assemblages suggests that the community will only recover once the aquifer, channel margins and hyporheic zones are fully saturated (Stubbington et al., 2009). ***The significance of antecedent conditions and 'drought history' to sampled macroinvertebrate assemblages cannot be overstated***.

The Agency's approach to specifying flow thresholds for the River Itchen is based on the assumption that summer low flows are the most important determinant of invertebrate communities (LIFE scores) observed in the following spring. Hence, the affect of intervening winter high flow spates was not explicitly incorporated within their assessment of target flows. Furthermore, ***the assumed relationship between LIFE scores and antecedent flow is based on behaviour within a single water year; so this relationship may not be representative of progressive ecological deterioration that could arise from multi-year droughts***.

Using a two-season regression model for predicting spring LIFE scores, and supplementary analyses of gauged river flows, it is shown that:

- Compliance with a long-term average summer Q95 (Target 1) flow of 262 Ml/d at MU5 will be impossible to assess in real-time. This is because the flow statistic has to be calculated from a moving window of several years' gauged flows.
- A summer Q95 "hands off" (Target 2) flow of 198 Ml/d fails to deliver the annual summer Q95 (Target 3) flow of 237 Ml/d. In other words, there is dependency between the flow targets at a given site.
- A Target 2 flow of 224 Ml/d is on average needed to achieve the annual summer Q95 (Target 3) flow of 237 Ml/d in MU5. This estimate assumes that the long-term ratio between the minimum flow and summer Q95 has not been changed by abstractions.
- A Target 3 flow of 237 Ml/d might not achieve environmental objectives on average one year in 11 depending on the magnitude of winter Q5 flows. In other words, there is a dependency between the flows of successive seasons and ecological outcomes.
- Historically when there has been good invertebrate status in the upper and middle Itchen, a minimum summer flow of at least 289 Ml/d is expected in the lower river.
- The empirical relationship between invertebrate status and antecedent flows may not necessarily hold for the future if other conditions in the river change such as water temperature or sediment load.

Projected climate change towards drier summers and wetter winters would reshape the intra-annual flow regime and hence the potential for aquifer recharge and recovery of drought-stressed macroinvertebrate communities. Therefore, ***it is recommended that any revision to existing targets and/or extension of macroinvertebrate assessment to other catchments should incorporate the effects of both winter and summer flows***.

In summary, the proposed Stage 4 Target flow regime based on summer Q95 flows may be regarded sufficiently precautionary provided that failure to achieve environmental objectives one year in 11 is an acceptable level of risk. However, this conclusion is tempered by two important caveats. First, the Target 2 flow should be revised upwards to ensure that the existing Target 3 flow can be achieved. Second, there should be sufficient flexibility in water governance structures and across the abstraction licensing regime to adaptively manage targets should seasonal flows begin to shift in response to climate and/or land use change.

Beyond the 2040s, there is increasing likelihood that the current set of target flows will not protect invertebrate communities (and hence the wider ecosystem) in a significant proportion of years. In the interim, changes in thermal and water quality regimes are expected to add to existing pressures on the river's ecosystem. For instance, ocean warming could impact survival rates of salmon in their marine stage.

Finally, having reviewed the Agency's approach to defining target flow thresholds in the Itchen it is acknowledged that the abundance of ecological and (long-term) hydrological data provides a strong starting point. However, there remain wider questions about the transferability of the methodologies to more data-sparse rivers.

Acknowledgements

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Annex 1 Standardized winter (October to March) Q5 flows in the River Itchen

WINTER FLOWS (STANDARDIZED BY 1987-2001 MEAN)						
Q5	**MU1**	**MU2**	**MU3**	**MU4**	**MU5**	**MU6**
1977	1.12	1.20	0.94		1.16	
1978	0.76	0.98	0.78		0.87	
1979	0.76	0.92	0.68		0.83	
1980		0.96			0.79	
1981		0.80			0.77	
1982	0.81	1.03	0.89		0.87	
1983	1.03	1.13	1.06	0.00	1.14	1.22
1984	0.78	0.98	0.78	0.94	0.86	0.85
1985	0.72	0.93	0.84	0.98	0.90	1.00
1986	0.82	0.93	0.76	0.96	0.90	1.05
1987	0.70	0.86	0.74	0.86	0.80	0.86
1988	1.13	1.09	0.99	1.14	1.09	1.10
1989	0.56	0.73	0.57	0.73	0.65	0.67
1990	1.23	1.07	1.13	1.22	1.28	0.96
1991	0.52	0.72	0.52	0.59	0.65	0.67
1992	0.26	0.54	0.31	0.47	0.44	0.39
1993	0.85	1.00	0.90	0.94	0.94	0.94
1994	1.39	1.21	1.50	1.21	1.27	1.35
1995	1.63	1.41	1.39	1.48	1.45	1.21
1996	0.61	0.84	0.73	0.82	0.82	0.88
1997	0.53	0.74	0.55	0.68	0.65	0.71
1998	0.73	0.82	0.59	0.78	0.85	0.90
1999	1.26	1.21	1.17	1.31	1.22	1.25
2000	0.77	0.96	0.81	0.99	0.89	0.95
2001	2.82	1.80	3.11	1.78	2.01	2.16
2002	0.83	1.03	0.97	0.99	0.92	0.92
2003	1.89	1.44	1.68	1.64	1.57	1.72
2004	0.84	0.93	0.88	0.95	0.93	0.93

Annex 2 Standardized summer (April to September) Q95 flows in the River Itchen

SUMMER FLOWS (STANDARDIZED BY 1987-2001 MEAN)						
Q95	**MU1**	**MU2**	**MU3**	**MU4**	**MU5**	**MU6**
1976	0.45	0.56	1.00		0.63	
1977	1.25	1.09	1.07		1.19	
1978	1.17	1.12	1.17		1.12	
1979	2.00	1.30	1.28		1.41	
1980		1.02			1.00	
1981	0.99	1.09	0.96		1.20	
1982	1.01	0.97	1.06		1.00	0.81
1983	1.44	1.13	1.53		1.17	1.12
1984	1.21	0.97	0.98	0.98	0.97	1.05
1985	1.08	0.94	1.10	1.11	1.08	1.15
1986	1.10	0.97	1.05	1.07	1.05	0.96
1987	1.09	0.99	1.08	1.02	1.04	1.09
1988	1.05	1.01	1.05	1.11	0.99	0.97
1989	0.77	1.03	0.96	0.84	0.82	0.96
1990	0.92	0.97	0.99	0.94	0.91	0.77
1991	0.86	0.89	0.85	0.89	1.06	0.95
1992	0.65	0.69	0.56	0.69	0.70	0.67
1993	1.06	0.97	0.86	0.95	1.02	0.99
1994	1.00	0.99	0.98	0.97	1.01	0.94
1995	1.01	1.13	1.03	1.04	0.94	0.85
1996	0.82	0.88	0.89	0.92	0.88	0.87
1997	0.76	0.79	0.70	0.76	0.75	0.79
1998	1.05	0.95	0.89	0.94	1.04	1.15
1999	1.06	1.04	0.98	1.03	1.01	1.15
2000	1.48	1.22	1.48	1.35	1.43	1.49
2001	1.42	1.44	1.69	1.56	1.40	1.38
2002	1.29	1.09	1.36	1.24	1.21	1.26
2003	1.05	1.04	1.20	1.07	1.04	1.00
2004	1.01	0.93	1.01	1.02	1.00	1.03

Annex 3 Multiple linear regression model for estimating standardized LIFE scores in spring at sites in the River Itchen.

Regression Statistics	
Multiple R	0.77
R Square	0.59
Adjusted R Square	0.58
Standard Error	0.02
Observations	70

ANOVA	*df*	*SS*	*MS*	*F*	*Significance F*
Regression	2	0.0314	0.0157	48.5251	0.0000
Residual	67	0.0216	0.0003		
Total	69	0.0530			

Model	*Coefficients*	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	0.9269	0.0112	83.0292	<0.0001	0.9047	0.9492
Su Q95 standard	0.0423	0.0120	3.5151	0.0008	0.0183	0.0663
Wi Q5 standard	0.0261	0.0048	5.4193	<0.0001	0.0165	0.0357